AN ASSESSMENT OF BASIN DEVELOPMENT AND COAL RANK IN THE KAITANGATA COALFIELD, SOUTH OTAGO, NEW ZEALAND.

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Frontispiece

The Barclay coal horizon exposed at Coal Point, Kaitangata Sector.

ABSTRACT

The Kaitangata Coalfield, South Otago is located on the western boundary of the Great South Basin. It is comprised of conglomerate, sandstone, mudstone and coal belonging to the Late Cretaceous to Early Paleocene aged Taratu Formation. The Taratu Formation contains in excess of 16 coal seams (many of which are economically significant). The deposits were analysed to evaluate the relative influence facies relationships, burial depth, syn and post depositional faulting and the intrusion of the Miocene Dunedin Volcanics on coal rank.

A basin-specific lithological coding system allowed the stratigraphic reconstruction of the Kaitangata Coalfields architecture via cross-sections and coal thickness isopach maps. This showed the basin development could be divided into three phases. The Lower Taratu Members are comprised of greywacke conglomerate and coal which was deposited in an alluvial fan setting by the basin bounding Castle Hill Fault scarp. The Middle Members are composed of quartz conglomerates and coal and were deposited in a lower delta plain to marginal marine environment. Localised paloehighs still provided greywacke clasts in some areas, with the Castle Hill Fault still the main bounding fault. The Upper Taratu Members were deposited in a lower delta plain but across a much broader basin overtopping the Castle Hill Fault onto the previous adjacent paleohigh.

The Kaitangata Coalfield is best described as a Late Cretaceous rift basin in which the deposition of the basal Henley Breccia and Lower Taratu Formation were the result of synrift basin controls from the Castle Hill Fault. The Middle Taratu Formation represents the transition between syn and post rift basin development, whereas, the Upper Taratu Formation represents post-rift thermal subsidence. Other allogenic controls such as climate and eustacy also influenced on basin development

A study of coal rank study utilised a total of 31 samples for vitrinite reflectance (VR), 8 for vitrinite and inertinite reflectance, and 8 for coal chemistry. An additional 336 coal chemical analyses were compiled from previous drilling reports and corrected to a dry,

mineral matter, sulphur free basis (dmmsf). Coal rank was assessed using VR, Calorific Value (CV) and Volatile Matter (VM). VR showed an overall increase in rank with depth in the Kaitangata Sector of 0.037/100m, whereas the Benhar showed a negligible Downhole VR increase over 300m. However, CV showed an average linear downhole rank increase in the Benhar Sector of 469Btu/lb/100m, and a trend of 505Btu/lb/100m in the Kaitangata Sector. Lateral rank trends showed that coal rank increased towards the Castle Hill Fault in the Benhar Sector, whereas rank in the Kaitangata Sector showed localised rank increases. Rank trends across the coalfield are best explained primarily as the result of depth of burial processes; however, fluid flow along faults and volcanic intrusions may have also had local effects on coal rank.

TABLE OF CONTENTS

Abstract ... i
Table of Contents ... iii
List of Figures ... vi
List of Tables ... ix
List of Appendices ... x
Acknowledgements ... xi

Chapter One INTRODUCTION

1.1 INTRODUCTION ... 1
1.2 THE KAITANGATA COALFIELD ... 2
1.3 HISTORY OF RESEARCH ... 5
1.4 RESEARCH AIMS ... 8

Chapter Two METHODOLOGY

2.1 INTRODUCTION ... 10
2.2 STRATIGRAPHIC ANALYSIS TECHNIQUES ... 10
2.2.1 Drillhole Data Analysis ... 10
2.2.1.1 Characterising Coalfield Lithotypes ... 11
2.2.2 Cross-section Development and Interpretation ... 13
2.2.3 Coal and Carbonaceous Mudstone Isopach Maps ... 13
2.3 SAMPLE COLLECTION ... 13
2.3.1 Field Sample Collection ... 14
2.3.2 Drillcore Sample Collection ... 14
2.4 COAL ANALYTICAL METHODS ... 15
2.4.1 Vitrinite Reflectance ... 19
2.4.1.1 Coal Pellet Preparation ... 20
2.4.1.2 Vitrinite Reflectance Technique ... 20
2.4.1.3 Vitrinite and Inertinite Reflectance Fluorescence ... 22
2.4.2 Coal Chemistry ... 22
2.4.2.1 Volatile Matter ... 23
2.4.2.2 Calorific Value (Specific Energy) ... 23
2.4.2.3 Corrections ... 23
2.4.2.4 Laboratory Error ... 24
2.4.3 Suggate Rank Plots ... 25
2.4.3.1 Suggate Rank and Ash Content ... 25

Chapter Three STRATIGRAPHY

3.1 INTRODUCTION ... 27
3.2 STRATIGRAPHIC OVERVIEW ... 28
3.2.1 Caples Group (Basement) ... 28

3.2.2 Henley Breccia 28
3.2.3 Taratu Formation 29
3.2.4 Wangaloa Formation 30
3.2.5 Dunedin Volcanic Group 30
3.3 STRATIGRAPHIC ANALYSIS OF THE TARATU FORMATION 31
3.3.1 Previous work on the Taratu Formation 31
3.4 STRATIGRAPHIC ANALYSIS IN THIS THESIS 36
3.4.1 Revision of Stratigraphy 36
3.4.2 Lower Taratu Members 37
3.4.3 Middle Taratu Formation 40
3.4.4 Upper Taratu Members 51
3.5 DEPOSITIONAL ENVIRONMENT OF THE TARATU FORMATION 56

Chapter Four RANK TRENDS

4.1 INTRODUCTION 58
4.1.1 Coal Rank: Background 58
4.1.1.1 Vitrinite Reflectance 59
4.1.1.2 Calorific Value and Volatile Matter 61
4.2 RANK TRENDS IN THE KAITANGATA COALFIELD 61
4.2.1 Kaitangata Sector Downhole Rank Trends 62
4.2.1.1 Drillhole 3064 62
4.2.1.2 Drillhole 3055 64
4.2.1.3 Drillhole 3057 65
4.2.2 Lateral Rank Trends, Kaitangata Sector 66
4.2.2.1 Kai Main Coal Horizon 66
4.2.2.2 Jordan Coal Horizon 68
4.2.2.3 Capstick Coal Horizon 70
4.2.2.4 Broome Coal Horizon 70
4.2.2.5 Kaituna Coal Horizon 72
4.2.2.6 Barclay Coal Horizon 74
4.2.2.7 Washpool Coal Horizon 77
4.2.3 Benhar Sector Downhole Rank Trends 79
4.2.3.1 Drillhole 3050 79
4.2.3.2 Drillhole 3052 80
4.2.3.3 Other Members with Limited Data 81
4.2.4 Lateral Rank Trends, Benhar Sector 82
4.2.4.1 Penman Coal Horizon 82
4.2.4.2 Benhar Coal Horizon 84
4.2.4.3 Mount Wallace Coal Horizon 86
4.2.4.4 Coombe Hay Coal Horizon 88
4.2.5 General Rank Trends 88
4.3 INTERPRETED THERMAL HISTORY 90
4.3.1 Causes of Downhole Rank Trends 91
4.3.1.1 Burial 91
4.3.2 Causes of Lateral Rank Trends 92
4.3.2.1 Burial 93

4.3.2.2 Fluid Flow along Faults 93
4.3.2.3 Volcanic Intrusives 94
4.3.3 Sources of Unexplained Variation 94
4.3.3.1 Coal Type Variation 94
4.3.3.2 Maceral Identification and the use of Telovitrnite 95
4.3.3.3 Coal Chemistry 95
4.3.4 Synthesis of Thermal History 96

Chapter Five BASIN OVERVIEW

5.1 INTRODUCTION 97
5.1.1 Background: Mid-Cretaceous Rifting 97
5.1.2 Characterising the Kaitangata Basin 99
5.1.3 Introduction to Rift Basin Models 100
5.2 BASIN DEVELOPMENT IN THE KAITANGATA COALFIELD 105
5.2.1 Henley Breccia 106
5.2.2 The Lower Taratu Members 107
5.2.3 The Middle Taratu Members 107
5.2.4 The Upper Taratu Members 109
5.2.5 Wangaloa Formation 110
5.3 THE CRETACEOUS PAKAWAU SUB-BASIN (TARANAKI BASIN) 110
5.4 COMPARISON OF THE KAITANGATA COALFIELD TO THE PAKAWAU SUB-BASIN 114
5.5 OTHER CONTROLS ON BASIN DEPOSITION 116
5.6 SUMMARY 119

Chapter Six DISCUSSION

6.1 SYNTHESIS OF ANALYSES 120
6.2 FUTURE RESEARCH 124
6.3 SUMMARY 124

LIST OF FIGURES

Chapter One INTRODUCTION

1.1 Regional Geology of South Otago 3
1.2 Regional fault map of the South Otago area 4

Chapter Two METHODOLOGY

2.1 Sampling of coal at the Kai Point Opencast Mine 15
2.2 Location map of samples for vitrinite reflectance and coal chemistry analyses in the Kaitangata Sector 17
2.3 Location map of samples for vitrinite reflectance and coal chemistry analyses in the Benhar Sector 18
2.4 Relationship between the three main coal maceral groups 20
2.5 Random reflectance is the measurement of a coal macerals reflectance regardless of its orientation 21
2.6 The three standards for VR calibration: the sapphire, YAG and 5-glass standards 21
2.7 Suggate Rank plot classification modified from Suggate 2000 26

Chapter Three STRATIGRAPHY

3.1 Stratigraphy of the Taratu Formation in relation to regional geology 27
3.2 Coal isopach map of deposition during the Kai Main Member 41
3.3 Coal isopach map of deposition during the Capstick Member 42
3.4 Conglomerate percentage isopach map of the Lower Taratu Members 43
3.5 A schematic block diagram of deposition during the Kai Main Member in the southern portion of the Kaitangata Coalfield 44
3.6 Model of a coarse grained, shallow water alluvial fan from the Upper Carboniferous of northern Spain 44
3.7 Coal isopach of deposition during the Muir Member times 46
3.8 Coal isopach of deposition during the Washpool times 47
3.9 Sulphur variation between the Jordan and Capstick seams (lower Members) and the Kaituna and Barclay seams (Middle Members) 49
3.10 Coal sulphur percentage map with known dinoflagellate occurrences in the Barclay Member 50
3.11 Schematic base diagram of the deposition during Muir deposition 50
3.12 A modern humid climate alluvial delta, the Yallahs fan delta, Jamaica 51
3.13 Coal and carbonaceous mudstone isopach distribution for the Mount Wallace coal horizon 53

3.14 Coal and carbonaceous mudstone isopach distribution for the Benhar coal horizon 54
3.15 Coal and carbonaceous mudstone isopach distribution for the Penman coal horizon 55
3.16 Base diagram of deposition during Benhar times 56

Chapter Four RANK TRENDS

4.1 Example of telovitrinite (the vitrinite submaceral used for measurement in this study) from the Jordan coal horizon, Drillhole 3064, Kaitangata Coalfield 60
4.2 Relationship between depth, vitrinite reflectance and calorific value in Drillhole 3064 63
4.3 Suggate Rank plot showing a progressive increase of rank with depth in the Taratu Formation Members of Drillhole 3064 64
4.4 Relationship between depth, vitrinite reflectance and calorific value in Drillhole 3055 65
4.5 Relationship between burial depth, vitrinite reflectance and calorific value in Drillhole 3057 66
4.6 Calorific Value (CV) isopach map for the Kai Main coal horizon 67
4.7 Suggate Rank plot (CV-VM) showing lateral rank variation of the Kai Main Member in various drillholes 68
4.8 Calorific Value (CV) isopach map for the Jordan coal horizon 69
4.9 Suggate Rank plot of lateral rank variation in the Jordan coal horizon 70
4.10 Calorific Value (CV) isopach map for the Capstick coal horizon 71
4.11 Suggate Rank plot showing lateral variation in the rank of the Capstick coal horizon 72
4.12 Calorific Value (CV) isopach map for the Kaituna coal horizon 73
4.13 Suggate Rank plot of the Kaituna coal horizon showing little lateral variation, but more type variation 74
4.14 Calorific Value (CV) isopach map for the Barclay coal horizon 75
4.15 Location of known Miocene volcanic intrusions and faults relative to Calorific Value trends within the Barclay coal horizon 76
4.16 Suggate Rank plot of lateral rank variability in the Barclay coal horizon 77
4.17 Calorific Value (CV) isopach map for the Washpool coal horizon 78
4.18 Suggate Rank plot of the Washpool coal horizon showing little lateral variability in rank 79
4.19 Comparison of down hole trends for drillhole 3050 between, vitrinite reflectance and calorific value with depth 80
4.20 Comparison of down hole trends for drillhole 3052, between vitrinite reflectance and calorific value 81
4.21 Combined plot of coals within insufficient data for trend analysis 82
4.22 Calorific Value (CV) isopach map for the Penman coal horizon 83
4.23 Suggate Rank plot of the Penman coal horizon showing little rank and type variability in the member 84
4.24 Calorific Value (CV) isopach map for the Benhar coal horizon 85

4.25 Suggate Rank plot of lateral and type variation in the Benhar coal horizon 86
4.26 Calorific Value (CV) isopach map for the Mount Wallace coal horizon 87
4.27 Suggate Rank plot of the Mount Wallace coal horizon showing rank and type variation 88
4.28 Suggate Rank plot of selected Benhar Sector coals, showing a stratigraphic increase in rank 89
4.29 Suggate Rank plot of selected Kaitangata Sector coals showing a stratigraphic increase in rank, but over less range than the Benhar Sector coals 90
4.30 Maximum geothermal gradient of the Kaitangata Coalfield 92

Chapter Five BASIN OVERVIEW

5.1 A comparison between, (a) a mantle generated rift and (b) a lithospheric generated rift 101
5.2 The Texas longhorn model 104
5.3 Basin development stages 105
5.4 Location, structure and lateral distribution of the Pakawau Group onshore sediments 111
5.5 Late Cretaceous reconstruction of the New Zealand continent 118
5.6 Latest Cretaceous reconstruction of the New Zealand continent 118
5.7 Relationship between Pakawau Formation Members biostratigraphic indicators, sea-floor spreading and eustatic sea-level curves 119

LIST OF TABLES

Chapter Two METHODOLOGY

2.1 Sedimentary Rock Types and Codes used for the Kaitangata Coalfield 12
2.2 Summary of analyses preformed on Kaitangata coals in this study 16
2.3 Proportion of analyses preformed on Taratu Formation coals in this study 16

Chapter Three STRATIGRAPHY

3.1 Classification of Taratu Formation Members 32

LIST OF APPENDICES

Appendix A CROSS SECTIONS (Kaitangata and Benhar Sectors) 138

Appendix B COAL ISOPACH MAPS 139

Appendix C VITRINITE REFLECTANCE 155

Appendix D VITRINITE & INERTINITE REFLECTANCE FLUORESENCE (VIRF) 169

Appendix E DATA CD: An Assessment of Basin Development and Coal Rank in the Kaitangata Coalfield 175

Appendix F LOCATION OF DRILL HOLE AND OUTCROP SAMPLES 177

Appendix G SUGGATE RANK PLOTS 188

Appendix H LOGPLOT LITHOLOGICAL PATTERNS 195

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CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Studies of sedimentary basins are conducted for many reasons. One of those reasons is in the assessment of hydrocarbon potential. The discovery and utilisation of liquid petroleum (oil) in the early 1900's fuelled numerous investigations that gave geology a broad understanding of not just where and why hydrocarbons are present but in the mechanisms of basin formation itself. It was in 10th century England, however, that the study of hydrocarbons really began (Freese, 2003). Those first miners recognised that not all coals were the same and that predicting outcrops of these "burnable rocks" could be useful. Although our understanding of hydrocarbon formation and distribution has greatly improved over the last millennium, our need remains basically the same: to find, in the cheapest manner, the most accessable and useful coal, oil or gas deposits.

In modern day New Zealand, finding energy resources is still an issue (Saha, 1995; Navaratnam, 2003). New Zealand is currently a net energy importer and the oil and gas resources currently utilised, such as the Maui gas field, are depleting faster than expected (Patrick, 2003). However, for a small landmass New Zealand has incredibly large coal reserves of almost every maturity level (i.e. lignite to low volatile bituminous). The distribution and rank of these deposits was largely defined in a Government-led drilling programme initiated in the 1980's (McClelland, 1984; Browne, 1986; Duff and Barry, 1989). However, much of this data from some of the explored basins has not been examined in more than a cursory manner.

One such coal basin is the Kaitangata Coalfield which has extensive coal-bearing strata that vary in rank from lignite to sub-bituminous. Although some seams have been mined from the late 1800's, this commercially viable basin has not been analysed utilising the full synthesis of currently available data. Therefore, the purpose of this study is to understand the basin development of the Kaitangata Coalfield from the purpose of predicting the maturity and distribution of sedimentary facies.

1.2 THE KAITANGATA COALFIELD

The Kaitangata Coalfield is located approximately 80 kilometers southwest of Dunedin, New Zealand, and occurs over 45km^2, on the Western boundary of the Great South Basin (Figure 1.1). The Cretaceous-Early Paleocene aged Kaitangata Coalfield is situated within an extensively faulted belt in South Otago. Remnant Cretaceous normal faults from periods of extension, have been reversed due to transpressive tectonics during the Miocene (Raymond, 1985; Barry, 1985). This transpression has created areas of uplifted basement and sediments, as well as sediment bound structural depressions. The Kaitangata Coalfield is bound to the north by the convergence of the Tuapeka and Titri faults and to the east, by the northwest trending Tokomairiro Fault, which has been suggested by Raymond (1985) to be a continuation of the Tuapeka Fault (Figure 1.2). The Castle Hill Fault is thought to be a continuation of the Titri Fault (Lindqvist, 1998) and is the most prominent structural feature of the Kaitangata Coalfield. The Castle Hill Fault trends north and divides the coalfield into two sectors, the Kaitangata and Benhar Sectors (Figure 1.2).

The Kaitangata Sector encompasses coastal hills with elevations up to 330m (amsl) that decrease to broad flat Quarternary marine terraces and cliffs along the coastline (Harrington, 1958). Mid-Tertiary (Miocene?) reverse movement on the Castle Hill Fault along with associated compressional deformation have resulted in the hilly topography of the Kaitangata Sector. This deformation has resulted in the folding of the Kaitangata Sector into a large asymmetric anticline (Harrington, 1958). The western limb has a steep dip of 30 to 40° and an eastern limb with a shallower dip between 4 and 10°. Along the hinge of the anticline there are numerous minor faults with up to 50 meters of displacement that can be traced for up to 1.5km (Barry, 1985).

The Benhar Sector is a topographic low because of reverse movement of the Castle Hill Fault, and is folded into a low angle syncline, with minor faults displacing strata by up to 25m along the basin margins and through the axis of the syncline (Barry, 1985).

REGIONAL GEOLOGY OF SOUTH OTAGO

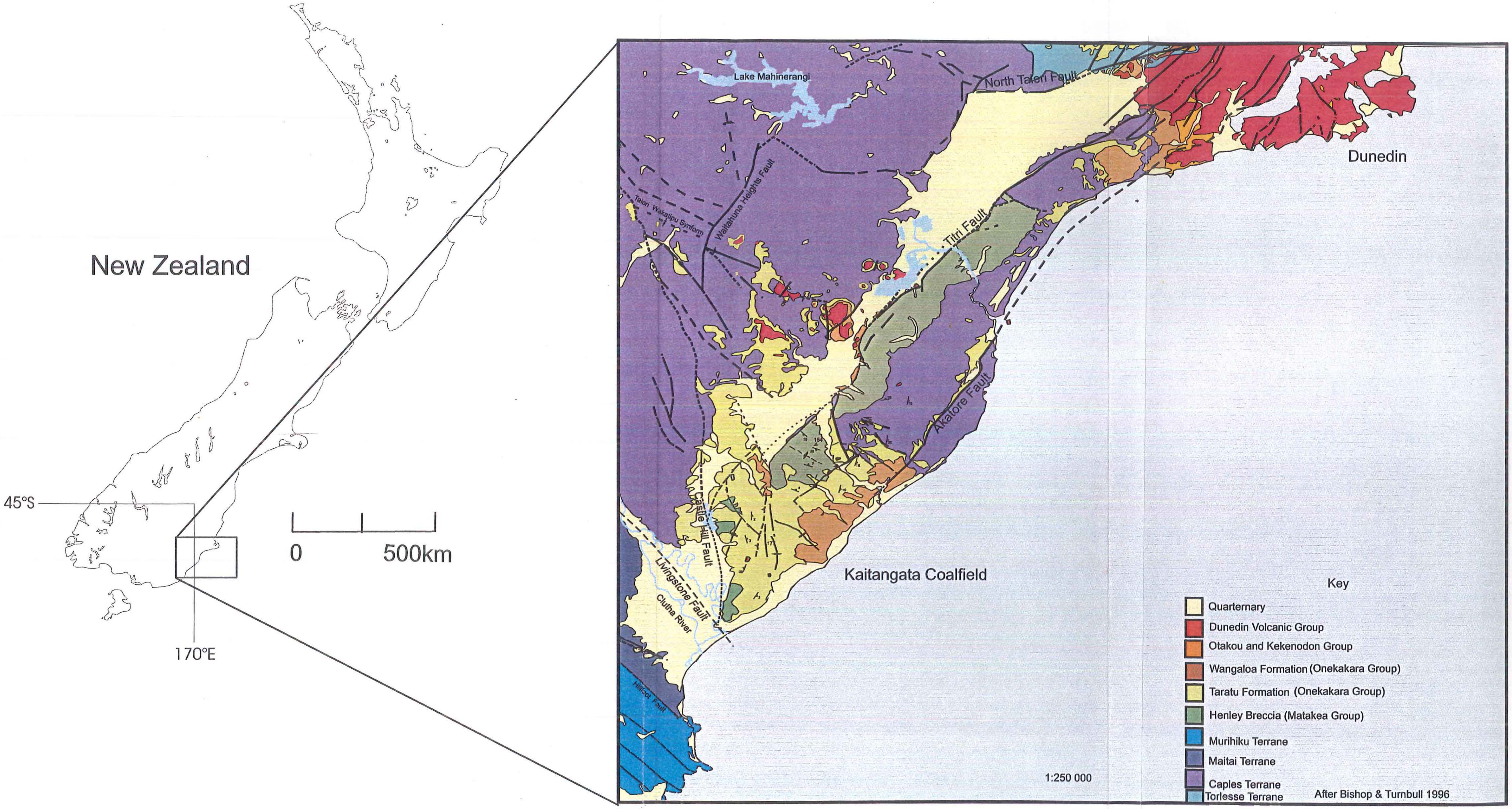


Figure 1.1: Regional Geology of South Otago

REGIONAL FAULT MAP OF SOUTH OTAGO

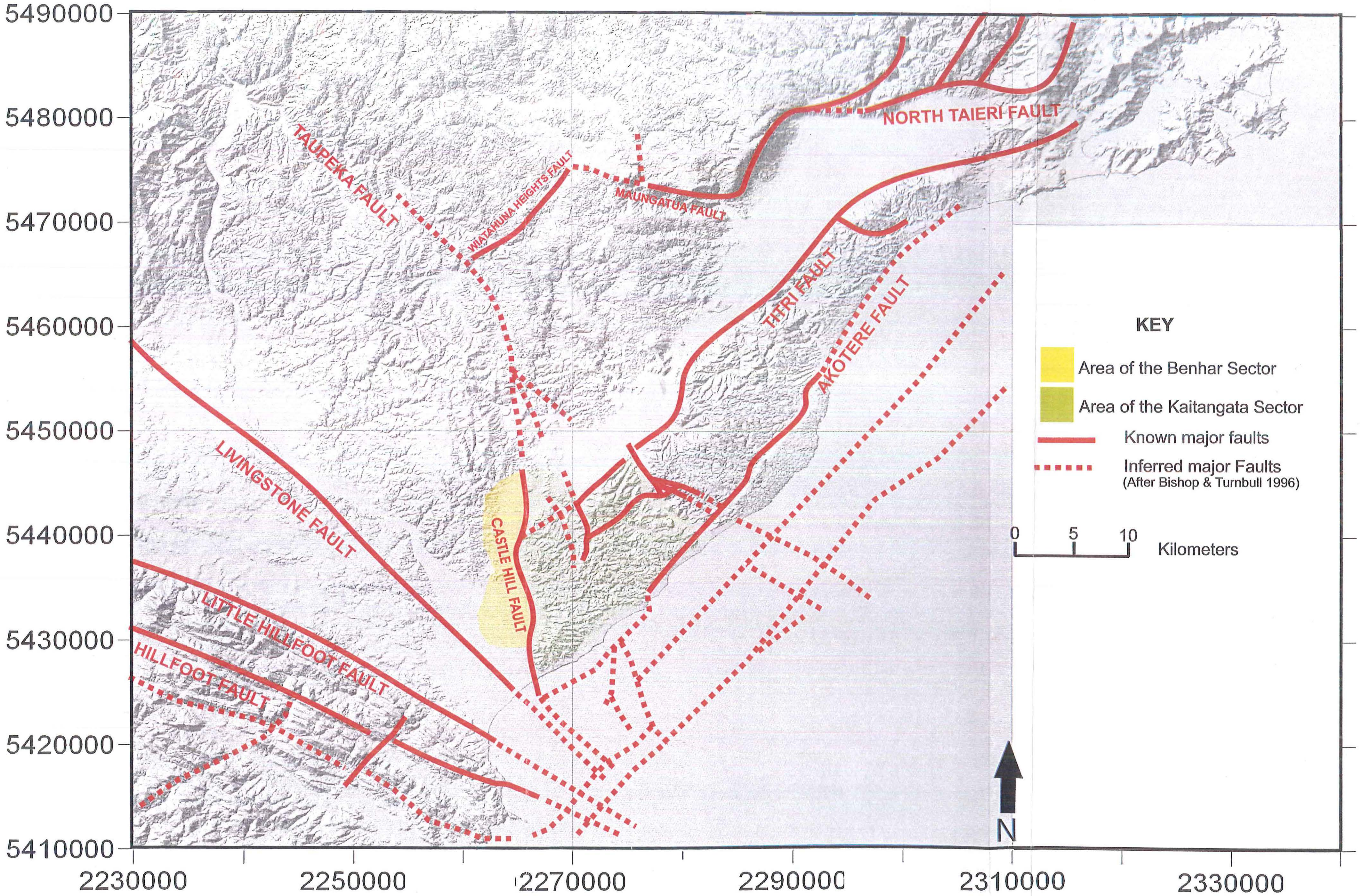


Figure 1.2 Regional fault map of the South Otago area

The Kaitangata Coalfield's sediments can be divided into three general stratigraphic groups:

1. The basal Henley Breccia,
2. The Taratu Formation,
3. The upper Wangaloa Formation.

Basement is comprised of non-schistose greywacke belonging to the Caples Group (formerly the Tuapeka Group). This is overlain by mid Cretaceous Henley Breccia, comprised of angular breccia interbedded with minor sandstones and carbonaceous mudstones (Harrington, 1958). This is unconformably succeeded by the latest Cretaceous-Early Paleocene Taratu Formation, which includes most of the sedimentary succession of the Kaitangata Coalfield (and will be the focus of this study). Lithologies are comprised mostly of conglomerate, sandstones and mudstones, as well as containing in excess of 16 economic coal bearing members ranging in thickness from <1m and up to 40m thick. The Taratu Formation interfingers with the overlying Early Paleocene Wangaloa Formation, which is a sequence of calcareious fossiliferous sandstones. These are all intruded by the Miocene aged Dunedin Volcanic Group (Harrington, 1958).

1.3. HISTORY OF RESEARCH

The Kaitangata Coalfield has a long history of research being conducted there dating from 1855. Most of this investigation was the result of the economic significance of the coalfield, but also partly because many of New Zealand's pioneer geologists such as Hutton, Hector and McKay resided or worked in Dunedin (Raymond, 1985).

From the early 1850's up until the 1950's, heated debates were initiated over the coalfield's age, origin, stratigraphy and structure. Lauder-Lindsay (1861) was one of the first people to observe that the sequence of coal bearing strata was probably much younger than the Otago Schists. Hutton (1866) published a report estimating the tonnage of the coalfield at greater than 100 million tonnes. Hutton (1872), and later Hutton and Ulrich (1875), further distinguished stratigraphic detail, noting that the coals were often covered by gravel, that the upper limits of the coals were eroded, and that the fragments of coal were incorporated into the overlying conglomerates. It was also noted that the economically important seams occurred in the south of the coalfield. Hector (1877) was the first to comment on the rank of Kaitangata coals, stating they were "semi-bituminous in rank" and had structures which made them notably similar to New South Wales coals (Raymond, 1985).

A range of ages were also speculated for the Kaitangata Coalfield. Hutton and Ulrich (1875) discussed ages of pre-Pleistocene for Benhar coals and Miocene for Kaitangata Sector coals. Hutton (1900) later suggested the coals were the oldest Tertiary rocks of New Zealand. This was refuted by Park (1910), who concluded that the coal measures were Late Cretaceous in age.

The stratigraphy of the coalfield has provided substantial confusion, with the stratigraphic succession of coals, underlying breccia, and overlying Wangaloa Formation often misinterpreted and arranged in various orders. Hector (1886) falsely interpreted that the Henley Breccia (which underlies the coal bearing Taratu Formation) was the lateral equivalent of the greywacke clast bearing Taratu Members, which he thought overlay the quartz conglomerate (when they in fact underlie the quartz conglomerate members).

Park (1910) interpreted the Wangaloa Formation as interbedded with quartz gravels with greywacke gravels overlying the sequence. This stratigraphy remained misunderstood, and was not refuted until Ongley (1924) corrected the relationship between the Taratu Members and the Wangaloa Formation.

Ongley (1939) provided the most comprehensive report on the structure, stratigraphy and age of the coalfield at the time. But like many of his contemporaries, he thought that the Benhar Sector coals to be a direct lateral equivalent of the Kaitangata Sector coals. He probably concluded this because he did not note the presence of the Castle Hill Fault. In addition, he postulated the Henley Breccia was a lateral equivalent to the Taratu Formation, an idea that stemmed from McKay (1894) who thought the Henley Breccia was fluvial conglomerates and the Taratu Formation was marine conglomerates. In Ongley's (1939) report detailing the geology of the coalfield, he notes the presence of igneous intrusions, in both mine workings and outcrop whilst mapping in the coalfield, and correctly attributed them to the volcanism associated with the Dunedin Volcanic Group.

Ongley's (1939) report provided the foundation for more extensive work on the coalfield in the 1940's. An objective of the New Zealand Geological Survey was in depth mapping of the Kaitangata Coalfield. Several geologists were included in this programme such as D. Jenkins and A. Mutch, who worked on data used in the Coal Resource

Survey's Report (Harrington, 1958). It was eventually completed by Harrington (1958) who defined the coal stratigraphy and corrected the relationship of the Henley Breccia and the Taratu Formation. Importantly he also noted the presence of the Castle Hill Fault, which was identified in the drive of the Castle Hill Mine by observing that fossiliferous Wangaloa Formation sediments that were juxtaposed with older Taratu Formation sediments, with a fault plane angle of ~60° between them. By addressing the importance of the Castle Hill Fault, and the numerous other faults, most of which were due to Tertiary deformation, Harrington (1958) proceeded to define the stratigraphy. This was hugely aided by the presence of exploration drillholes, large underground mines (e.g. Kaitangata and Castle Hill Mines) and several opencast mines (Taratu and Kai No. 1), which allowed Harrington the benefit of observing vertical and lateral stratigraphic relationships. This would have been useful, as apart from the coastal section of the coalfield, outcrop is limited.

Most of the mining activity in Kaitangata stopped between 1960-1974, as a result of a decline in the demand for Kaitangata coals with the increased utilisation of Ohai Coalfield's high rank low sulphur coals (Raymond, 1985). Lime and Marble Ltd. undertook exploration drilling between 1980-1985 for the Mines Division Coal Resources Survey (Browne, 1986). This began with two reconnaissance drilling programmes in which 46 drillholes were completed between 1980 and 1983, to intersect and assess the viability of shallow lignite deposits of less than 200m (Barry, 1982; McClelland, 1984). Between 1984 and 1985, another 16 holes were drilled to assess the deeper coal deposits in the southern Kaitangata Sector, as well as to assist with stratigraphic correlations (Browne, 1986). Reports defining the stratigraphy of the Benhar Sector and the middle Taratu Members of the Kaitangata Sector were completed by McClelland (1984), Barry (1985) and Duff and Barry (1989) in which significant emphasis was placed on defining the mining potential of different coal bearing Members as well as the basin limits and total coal resources. Barry (1985) and McClelland (1984) provided cross sections and seismic data which showed that there were several small basement faults in Benhar Sector, and approximately 300m of reversal on the Castle Hill Fault. McClelland (1984) also showed a distinct facies change in the Benhar Sector, with thick conglomeratic units in the northern sector and laterally equivalent fine muds and coals in the south (Raymond, 1985).

Raymond (1985) completed a MSc. thesis utilising drillholes from the drilling programmes in order to assess the paleoenvironmental interpretation for the Upper Taratu

Members. Raymond (1985) concurred that the Upper Taratu coals were latest Cretaceous to Early Paleocene in age.

Defining the age of the Taratu Formation has always been problematic. The only tentative age constraint that could be placed on the Taratu Formation has been using the presence of diagnostic tertiary fossils in the overlying Wangaloa Formation. It wasn't until Browne (1986), Browne and MacKinnon (1989), Crouch (1994) and Ward (1997) that diagnostic age constraints could be placed on the Upper Taratu Members by the means of palynology (in particular, pollen, spores and dinoflagellate analysis) which were primarily based on Raine's (1984) Cretaceous-Tertiary (K-T) zonation of Westland palynomorphs.

Browne (1986) completed a MSc. thesis assessing palynostratigraphy and placed the Cretaceous-Tertiary Boundary in the middle zone of the Benhar Member (Benhar Sector). Ward (1997) reevaluated Kaitangata K-T data and correlated it with the Greymouth Coalfield Cretaceous-Tertiary Boundary, but suggests that only one drillhole, DH 3030 (Benhar Sector) accurately depicts the K-T Boundary and other K-T bearing strata used by Browne (1986) are inconclusive (Ward, 2003 pers. comm.).

Lindqvist and Douglas (1987), and later Lindqvist (1998), have also contributed to the understanding of the Kaitangata Coalfield through facies analysis.

1.4 RESEARCH AIMS

The main aim of this thesis is to investigate the controls on coal maturation (rank) in the Kaitangata Coalfield, South Otago, New Zealand. This will be achieved by assessing whether coal maturation is related to 'normal' basin processes, such as subsidence and burial, or if it has been modified to some degree by syn or post-depositional faulting and/or volcanic intrusions. In order to accomplish the objective, the following goals will have to be met:

1) Create a stratigraphic framework to assess lateral continuity of seams,
2) Assess vertical and lateral coal rank trends in the Kaitangata Coalfield,
3) Provide an overview of the thermal and depositional evolution of the coalfield,
4) Delineate a basin history for the Kaitangata Coalfield.

These goals can be achieved through a combination of methodologies. Firstly, a depiction of the basin's architecture will be undertaken by delineating a lithostratigraphic framework. Secondly, this can then be applied to allow the vertical and lateral distribution of coal to be analysed and inferences made about its depositional setting. By applying coal rank indicators (coal compositional analysis) to the basins architecture, processes that may have influenced coal rank can be suggested.

This thesis is structured to firstly outline the stratigraphy and give a detailed assessment on the depositional environment within the Kaitangata Coalfield. Secondly, with an understanding of basin development, coal rank is assessed. This will be achieved using vitrinite reflectance and coal chemistry analysis, in particular, volatile matter and calorific value. Finally, the coalfield's basin development will be assessed and compared to the basinal evolution of the Pakawau sub-basin, a well studied New Zealand coal basin of the same age.

CHAPTER TWO

METHODOLOGY

2.1 INTRODUCTION

In order to assess the coal maturation trends in the Kaitangata Coalfield a number of datasets were integrated. Drillhole information was complied from New Zealand Coal Surveys Drilling Programme reports (e.g. Barry, 1982; McClelland, 1984; Barry, 1985 among others). These were then categorised and reinterpreted for lithotype to create stratigraphic columns, cross-sections and lithofacie maps (See Appendices A to G). Coal quality analysis from these reports were integrated into a single database and corrected to a dry mineral matter sulphur free basis (dmmsf) so that these analyses could be used for rank trend assessment. In addition to this data, samples were collected from outcrop and core stored in the Ministry of Economic Development (M.E.D) core storage facility in Dunedin; outcrop samples were analyses for proximate and ultimate analysis. Analysis of these samples were then added to the coal chemistry database (See Appendix E).Vitrinite Reflectance (VR) and Vitrinite and Inertinite Reflectance (VIRF) were performed on selected Kaitangata coal samples to provide additional rank control. Finally, additional rank information on samples were gleaned through plots using Suggate Rank curves.

2.2 STRATIGRAPHIC ANALYSIS TECHNIQUES

2.2.1 Drillhole Data Analysis

Stratigraphic analysis of the Kaitangata Coalfield primarily employed drillhole data as there is a lack of extensive outcrop in the study area. Drillhole data is available from previous drilling programmes in the Kaitangata and Benhar Sectors of the coalfield. This data includes early exploration maps and drillholes as well as data from the 1940-1950's when the large Castle Hill, Kaitangata and Explosion Mines were operative. In addition, drilling by Lime and Marble Ltd. in 1980-85 on behalf of the New Zealand Coal Resources Survey (NZCRS) provided the best data.

Most of the early drilling was conducted in the Kaitangata Sector, but most of this information has been lost or is incomplete. What has been preserved is published in Harrington (1958) and reports in Lime and Marble (Lime and Marble NZCRS 1982, 1984, 1985). Lime and Marble completed several drilling projects from 1980-1985 for New Zealand Coal Resources Survey. In total 46 drillholes were completed between 1980-1983 to determine reserves of shallow Taratu Members. A further 16 drillholes were completed between 1984-1985 to establish the extent of the lower Taratu Members. These Lime and Marble Reports provide excellent detail of lithology. The abundance of detailed drillhole information was utilised for cross-sections as well as coal and conglomerate thickness isopach maps.

2.2.1.1 Characterising Coalfield Lithotypes

An objective of this study was to characterise the clastic lithotypes of the Kaitangata Coalfield. This was necessary for interpretative purposes, as hundreds of drillholes were available. In order to determine coal rank variation within the Kaitangata Coalfield a stratigraphic framework was first needed. Although published cross-sections had been previously made (e.g. Harrington, 1958; McClelland, 1984; Barry, 1985; Lindqvist, 1998) it was thought prudent to source original logs for reinterpretation. To date, there has not been a comprehensive, coalfield-wide stratigraphic correlation.

Drillhole descriptions have been completed by numerous operators over a long time span. Before drillcore could be interpreted, descriptions given to lithologies required standardisation. Initially, 11 drillcores were entered into a database using English descriptions of the lithologies. A total of 573 lithologic units for those 11 cores were entered. These were then sorted based on grain-size, colour and sedimentary features. This allowed a grouping of most dominant lithotypes. Although this methodology is not as robust as procedures used for similar rock classification in New Zealand (e.g. Ferm and Moore, 1997; Ferm, *et al.* 2000) but it suited the scope of this study.

The groupings of lithologic units are given in Table 2.1, which also assigns a code for each rock type. This code was used as a quick method of logging and entering lithological data into computer-based spreadsheets which were linked to edited patterns in the software programme by Rockware$_{TM}$, Logplot 2001$_{TM}$. A pattern database in Logplot was created to represent every combination of lithologies shown in Table 2.1 (Appendix H). A total of 86 stratigraphic columns were created which encompassed both sectors of the coalfield (Appendix E).

Table 2.1: Sedimentary Rock Types and Codes used for the Kaitangata Coalfield.

Grain size	Colour	Code	Sedimentary Features	Code
CLAYSTONE	Black	11X	Massive	1X4
CLAYSTONE	Brown	12X	Bedded	1X5
CLAYSTONE	Green	13X	Root penetration	1X7
CLAYSTONE	Grey, Dark	14X	Carbonaceous	1XX.3
CLAYSTONE	Grey, Light	15X	Interbedded mst/silt	1X3
CLAYSTONE	Yellow	17X		
MUDSTONE/SILTSTONE	Black	31X	Massive	3X4
MUDSTONE/SILTSTONE	Brown	32X	Bedded	3X5
MUDSTONE/SILTSTONE	Green	33X	Root penetration	3X7
MUDSTONE/SILTSTONE	Grey, Dark	34X	Carbonaceous	3XX.3
MUDSTONE/SILTSTONE	Grey, Light	35X	Interbedded with sst-silt	3X3
MUDSTONE/SILTSTONE	Yellow	37X		
SANDSTONE	Green	53X	Interbedded with mst-silt	5X3
SANDSTONE	Grey, Dark	54X	Massive	5X4
SANDSTONE	Grey, Light	55X	Bedded	5X5
SANDSTONE	White	59X	Root penetration	5X7
			Carbonaceous	5XX.3
CONGLOMERATE	Green	73X	Monomictic	7X1
CONGLOMERATE	Grey, Dark	74X	Greywacke	7X1.1
CONGLOMERATE	Grey, Light	75X	Quartz	7X1.2
CONGLOMERATE	White	79X	Polymictic	7X2
			Interbedded	7X5
			Coal spars	7X3
COAL		020		
SOILS		002		
BASEMENT		003		

Based on 11 logs and a total of 573 lithological units.

2.2.2 Cross-section Development and Interpretation

Using stratigraphic columns created in Logplot, coals horizons were correlated across the coalfield. To best interpret the coalfields' stratigraphy it was decided to choose a laterally extensive horizon for each sector of the coalfield. This was necessary as significant postdepositional faulting and folding makes the reliability of seam identification by depth very poor in some areas. In addition, depositional/erosional patterns can be observed laterally in relation to the datum. Features such as truncations and erosion of coals, seam splitting and pinchouts were identified by using this method of analysis.

2.2.3 Coal and Carbonaceous Mudstone Isopach Maps

After stratigraphic correlations of Taratu Formation Members, isopach maps were created to show the lateral distribution and thickness of coal and carbonaceous mudstone for each of the Taratu Members. It was decided to combine coal and carbonaceous mudstones together as they both represent an organic-rich depositional environment. Coal/carbonaceous mudstone isopachs were done by correlating seams, then looking at vertical thickness in each drillhole. It was decided that in the case where coal is vertically separated by seam splits, that if the split could be correlated laterally then the carbonaceous material would be combined minus the split interburden to give a total thickness of the coal. Also, when drillhole density was very high in a particular area and there was no more detail to be gained by including all drillholes, the best drillhole was selected and the others were not included in the isopach map. All isopach maps can be found in Appendix B.

2.3 SAMPLE COLLECTION

Two types of coal samples were used in this study:

1) Field: With 3 trips made for sample collection
2) Drillcore: Two trips to the Ministry of Economic Development M.E.D. core storage facility, Dunedin New Zealand.

2.3.1 Field Sample Collection

Field samples were collected using a channel sampling technique to ensure the freshest and best representation of the seam. Firstly, the seam was visually assessed to note any characteristics of the coal which may affect the sample, such as high ash bands (mudstone parting) or areas of extensive weathering. Then the coalface was then cleaned back to minimise the effect of contaminated or altered coals in sampling, such as those affected by weathering. Once the face was clean, a channel sample was taken, beginning at the top of the seam and working to the bottom, attempting to remove a similar proportion of coal vertically. If there were obvious differences in coal quality throughout the seam, these areas have been sampled separately as plies (Figure 2.1). The coal was then dried and petrographic splits were taken by CRL Energy Ltd. The coal was then ground, and then sieved to ~1mm (0.0 phi). Due to the high proportion of low rank samples, all coals were dried in a 40°C oven overnight to remove any excess moisture. A list of grid references of sample localities can be found in Appendix F and field sample maps with locations of outcrop and drillcore samples in the Kaitangata Coalfield are presented in Figures 2.2 and 2.3.

2.3.2 Drillcore Sample Collection

Samples for vitrinite reflectance and chemical analyses were collected from two sources:
1) Drillcore stored in the (M.E.D.) core store in Dunedin,
2) Petrographic splits stored in the M.E.D sample store in Lower Hutt.

Samples collected from drillcore were collected by taking approximately 10cm of core from the targeted coal horizon, which was then dried and ground to 1mm, and sieved before being made into coal pellets. Unfortunately, there is a lack of drillcore kept from drilling programmes in Kaitangata, and only seams targeted for exploration have been kept in many cases.

The drillhole locations of drillcore sampled from the M.E.D core store as well as elevations and depths can be referred to in Appendix F. Maps of samples taken, by sector which includes the depths of samples can be referred to in Figure 2.2 and 2.3.

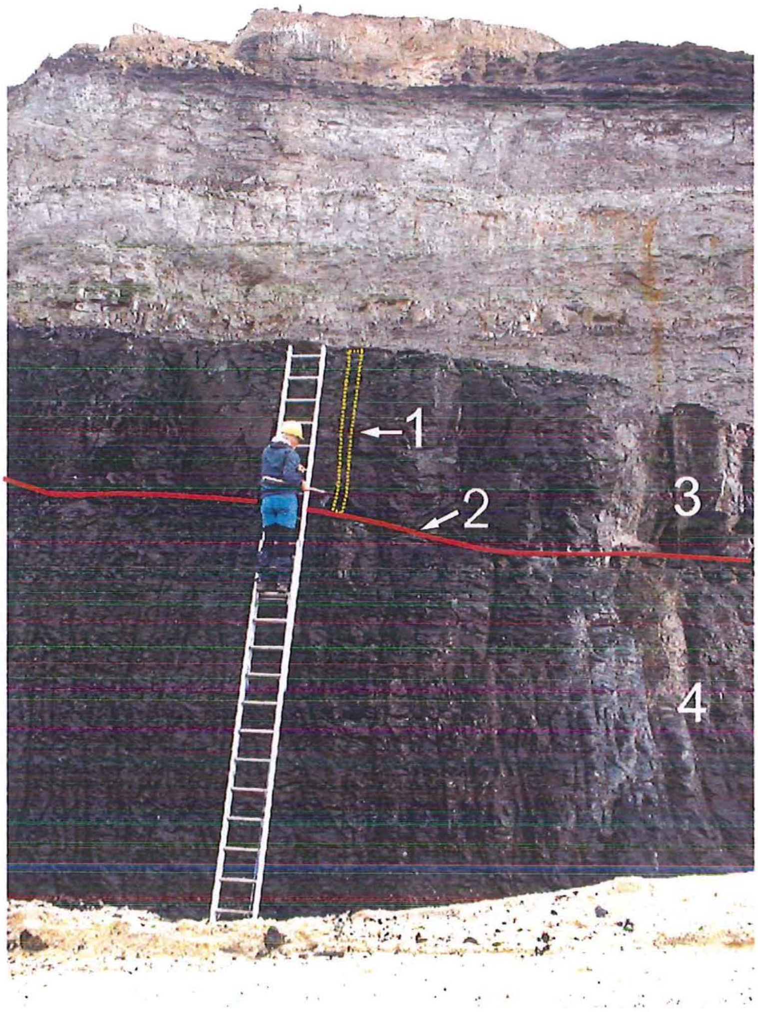


Figure 2.1: Sampling of coal at the Kai Point Opencast Mine. 1 (The area with the yellow border) refers to the area being prepared for the channel sample. 2 (The red line) shows a high ash band. This is used to separate the sampling areas of 3 and 4 The channel sample is continued in a straight line, however, samples 3 and 4 are bagged separately for analysis. (Photography by C.M. Nelson, 2002).

2.4 COAL ANALYTICAL METHODS

A total of 31 samples were analysed for VR, 8 for VIRF, and 8 were analysed for coal chemistry. An extra 336 coal chemical analyses were compiled from previous drilling reports (Barry, 1982; McClelland, 1984. Barry, 1985; Duff and Barry, 1985) (Table 2.2). This is further detailed in Table 2.3, which outlines the amount of samples and types of analysis done on each coal horizon.

Table 2.2 Summary of analyses preformed on Kaitangata coals in this study.

Analysis Type	Outcrop Sample	Drillhole Samples (Plies)
Vitrinite Reflectance	5	26
VIRF	1	7
Coal chemistry (Proximates and/or Ultimates)	8	336

Table 2.3: Proportion of analyses preformed on Taratu Formation coals in this study.

Taratu Member	Vitrinite Reflectance	VIRF	Coal Quality Analysis
Coombe Hay	-	-	1
Mount Wallace	2	1	16
Benhar	8	1	57
Penman	3	1	6
Fella	-	-	10
Washpool	-	-	16
Barclay	8	1	50
Kaituna	2	2	13
Cobweb	-	-	0
Muir	-	-	2
Broome	1	-	1
Capstick	2	1	12
Jordan	3	1	9
Kai Main	-	-	20
Carson	-	-	6
Shore and Older	-	-	0

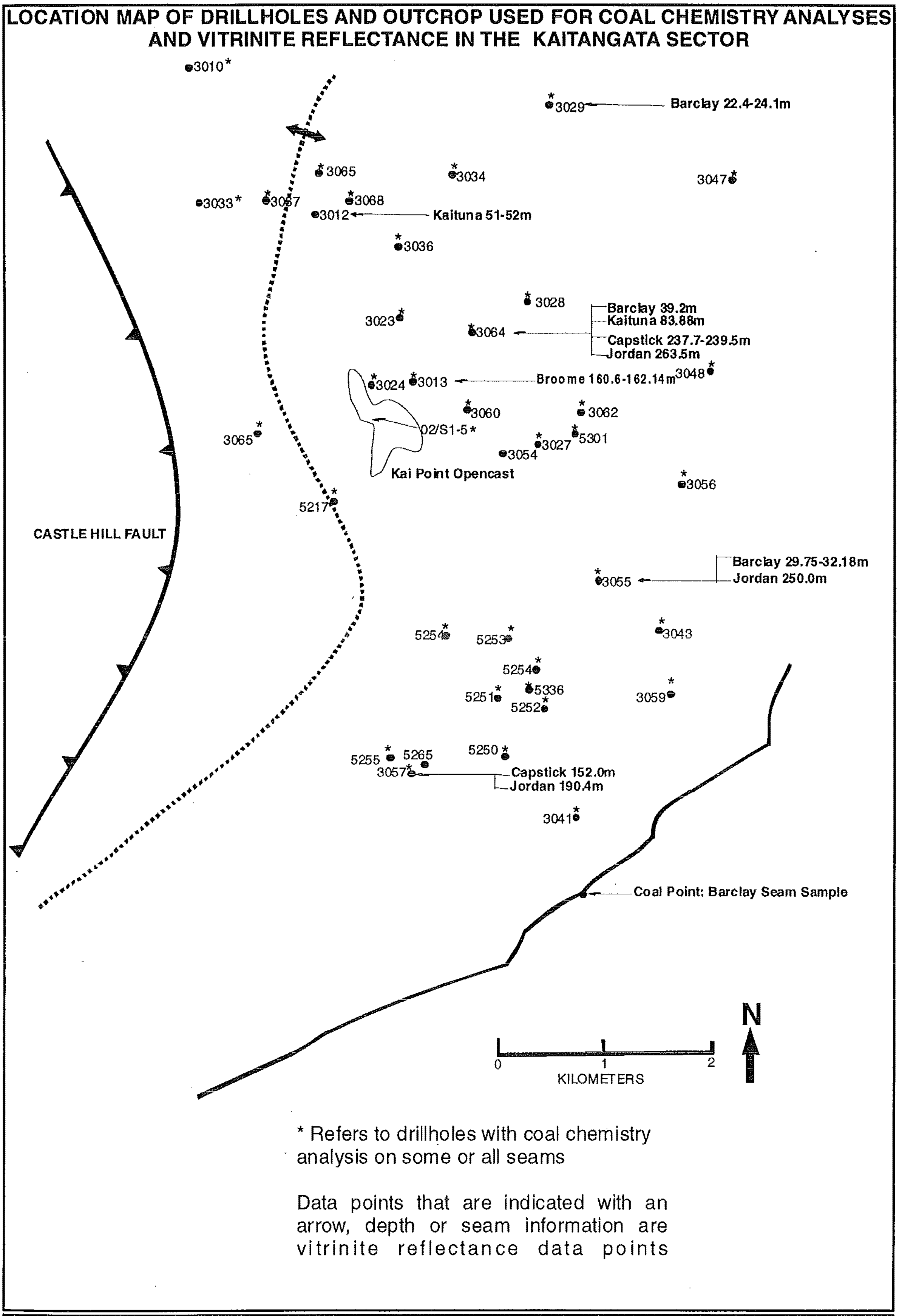


Figure 2.2: Location map of samples for vitrinite reflectance and coal chemistry analyses in the Kaitangata Sector.

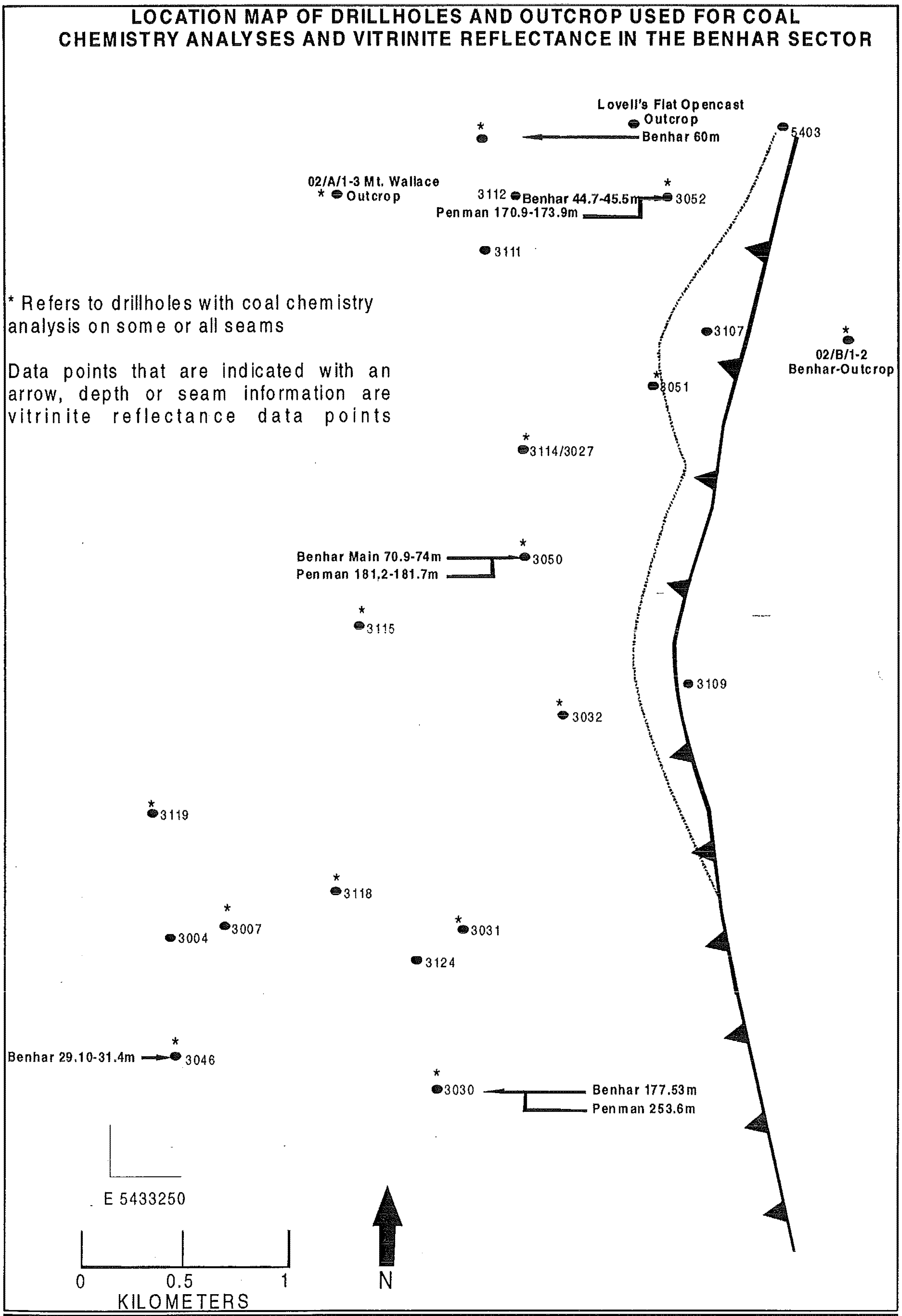


Figure 2.3: Location map of samples for vitrinite reflectance and coal chemistry analyses in the Benhar Sector.

2.4.1 Vitrinite Reflectance

The organic constituents of coal can be divided into microscopically recognisable groups called macerals (Teichmüller; *et al.*1998). These groups represent the remains of plants that have been preserved in coal and other rocks (Stach, *et al.*1982; Teichmüller; *et al.*1998).

Coal macerals can be divided into three primary groups:

1) liptinite (has been previously referred to as exinite)
2) vitrinite
3) inertinite

Microscopically, these macerals can be differentiated by their physical and chemical properties, which vary significantly between maceral groups. Liptinites are derived from relatively hydrogen rich plant remains, such as spores, waxes and fat, which results in a high fluorescence and low reflectance. Whereas, inertinites have a high carbon content, and a low hydrogen content often as the result of alteration of plant material by oxidisation. This is seen as a low fluorescence and a high reflectance. Vitrinites are composed of humic substances such as cell wall tissue, and have generally an intermediate hydrogen and carbon content which is much more stable over various ranks, and are thus, the preferred maceral for rank studies (Figure 2.4) (Teichmüller, 1998).

A Total of 31 samples were analysed for VR in this study (Table 2.2 and 2.3), with 13 samples of Benhar Sector and 16 Kaitangata Sector. Two samples of unknown coal samples were analysed from north of the Kaitangata Coalfield. The locations of these samples are in Appendix F and the VR results for these samples are in Appendix C.

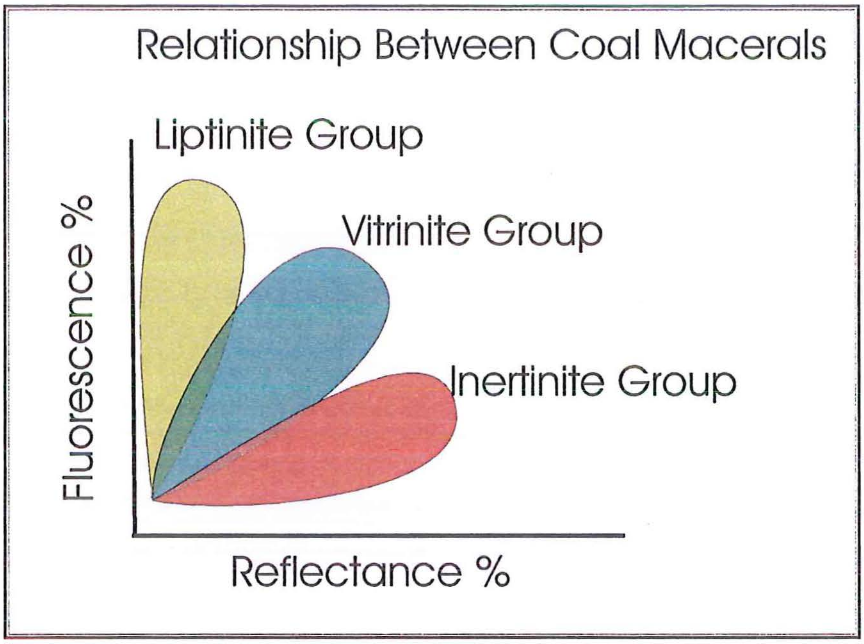


Figure 2.4: Relationship between the three main coal maceral groups. After Teichmüller, *et al.* (1998).

2.4.1.1 Coal Pellet Preparation

Coals were ground to 1mm and then dried at 40°C in an oven overnight before being mounted as resin pellets. Coals were mixed at a ratio of 20 grams of coal to 1:5 of Z606 hardener and Z105 resin. These were then placed in a plastic mould lubricated with vaseline and allowed to set overnight. Once the samples were removed from the moulds, they were left to stand for approximately 48 hour to cure, before being polished.

2.4.1.2 Vitrinite Reflectance Technique

It was decided after preliminary analysis on the coals (see Section 2.4.2) that telovitrinite would be the vitinite submaceral targeted for measurement in this study. According to International Committee for Coal and Organic Petrology (ICCP) telovitrinite is the most stable vitrinite submaceral for measurement as it is composed of gellified plant cells (Taylor, *et al.* 1998).

Random reflectance readings (Figure 2.5) were taken on coal pellets using a Zeiss UMSP 50 microscope with an attached berek illuminator (40x 0.85) polarising objective and a 0.16mm diaphragm pinhole. The photometer signal was calibrated using three standards, sapphire, glass and garnet (Figure 2.5). Each of these standards were cleaned using ethanol tissues to ensure accurate reading during calibration. Standards were manually adjusted and calibration measurements were obtained to be within ± 0.005% of each of the standards. To minimise fluctuations within the power supply, and random light contributing to measurements, lights were turned off during calibration and VR measurements. Each coal pellet was then measured for 50 VR. Calibration of the photometer signal was checked with each of the standards after each sample was completed. Each VR measurement was recorded to the Zeiss photometer programme at integration intervals of 0.5 seconds per reflectance reading. When 50 samples were achieved data was saved to floppy disk. The data was then exported to Microsoft Excel and checked for an error acceptability of ± 0.05%. If the error limit exceeded this, the sample would be re-examined.

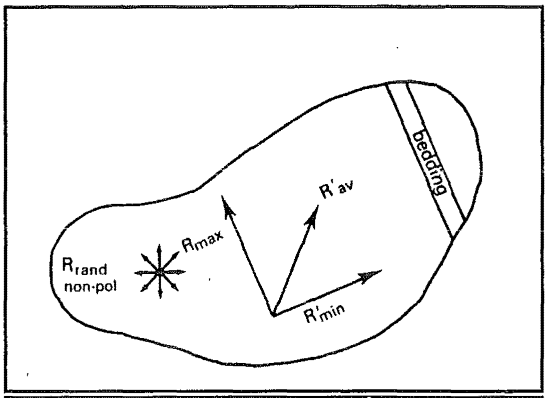


Figure 2.5: Random reflectance is the measurement of a coal macerals reflectance regardless of its orientation (Ward, 1984).

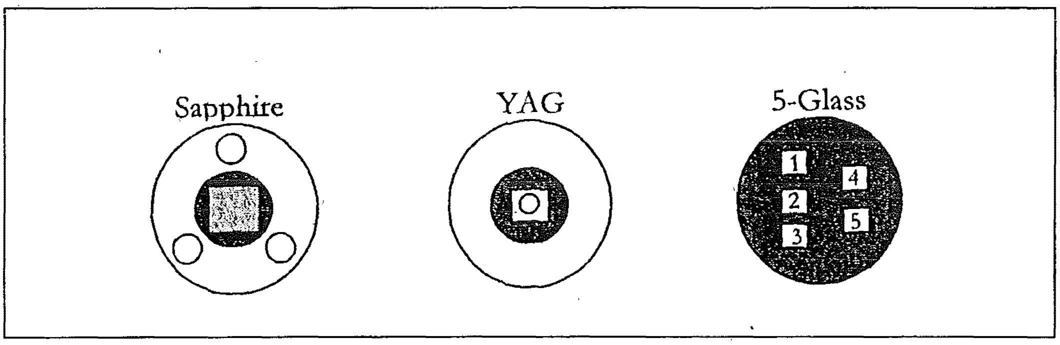


Figure 2.6: The three standards for VR calibration: The Saphire, YAG (Yiitruim Aluminium Garnet) and 5-Glass Standards (Eckersley, 1999).

2.4.1.3 Vitrinite and Inertinite Reflectance Fluorescence (VIRF)

Initially there was a concern that Kaitangata coals may be perhydrous (enriched in hydrogen). This is the result of changes occurring in the peat mire during or immediately after deposition (Stach, *et al.* 1982; Ward 1984; Teichmüller, *et al.* 1998). Perhydrous coals typically suppress vitrinite and may give a lower VR measurement for the true rank (Newman, *et al.*1998). Therefore, to determine if Kaitangata coals were perhydrous samples were assessed using Vitrinite and Inertinite Reflectance Flurescence (VIRF). VIRF is a technique that accommodates both coal type and rank variables by combining both reflectance and fluorescence measurements of vitrinite. Suppressed vitrinite corresponds to a high fluorescence of >6%, relative to the standard, whereas vitrinite of normal chemistry has a lower fluorescence of between 2-6% relative to the standard (Newman, *et al.* 2000). VIRF showed that the average coal type was not in excess of the standard and only anomalous measurements showed high fluorescence (refer to Appendix D). This indicated that on average, Kaitangata coals are not perhydrous. Dr. Jane Newman preformed all VIRF analyses, measuring fresh coal samples from outcrop and comparing these with coals obtained from a drillhole in each sector of the coalfield over the stratigraphic range of this study.

2.4.2 Coal Chemistry

Coal chemistry is a good indicator of coal rank as the chemical changes which occur in a coal as it undergoes maturation can be measured in a variety of laboratory analytical techniques. Data gained from such analyses provides insights into the depositional and thermal history of the coal. Eight coal chemistry analyses were collected from outcrop with an additional 336 collected from the following NZCRS drilling reports:

- Reconnaissance Drilling in the Kaitangata Coalfield Stage 1
- Reconnaissance Drilling in the Kaitangata Coalfield Stage 2
- New Zealand Liquid Fuels Trust Board: Assessment of the Kaitangata Coalfield.

These reports included information on the depth of the coal, which coal bearing member was intersected and the types of analyses performed on coal composition. This information was then entered into a database which divides the coals into seam plies, proximate and ultimate analyses (Appendix E).

This study uses coal quality analysis which have been corrected to a dmmsf basis removing the influence of moisture, mineral matter (volatile matter and ash), and sulphur, factors that are known to influence rank assessment.

The coal chemistry analyses used in this study are described below:

2.4.2.1 Volatile Matter

Volatile matter (VM) refers to the constituents of coal that are liberated at high temperatures not including the moisture content of the coal. This can include mineral moisture from clays and organic compounds from the coal itself. Typically, as a coal increases in rank the volatile matter component decreases due to a loss in porosity (Speight, 1982; Gray, 1983 Ward, 1984).

2.4.2.2 Calorific Value (Specific Energy)

The energy released from a coal when combusted is primarily due to the interaction of hydrocarbon compounds with oxygen (Ward 1984). The measurement of the energy released from the coal is known as its calorific value (CV) or specific energy. As a general rule, as the rank of a coal increases the calorific value also increases. In this study, the American Society for the Testing of Minerals (ASTM) reproducibility guidelines (ASTM D 5865) are used as the estimated error incurred through analytical methods. This is 164 Btu/lb for sub-bituminous coals and lignites (ASTM, 2002, Section 4).

2.4.2.3 Corrections

In many cases coal analytical data on Kaitangata coals existed as proximate analyses, with ultimate analyses only carried out on specific seams. Proximate Analyses are a measure of the coal's moisture (as received or air dried), volatile matter, ash, sulphur and calorific value (MJ/kg). These proximate analyses were converted to dry mineral matter sulphur free (DMMSF) and to Btu/lbs in the case of calorific value.

Suggate (1959) noted that New Zealand coals that had a high content of organic sulphur also had a higher VM content and a lower CV compared to coals which had a low total organic sulphur of an equitable rank. Thus, corrections were made to remove the influence of components of the coal such as mineral matter and sulphur, both of which affect the burning properties/temperature of the coal, and therefore calorific value of coals which in turn effects values used for rank assessment.

All coals for this study were corrected to dmmsf basins. The formulas used are given below:

1) $$\mathbf{\frac{CV\ (Btu/Lb)_{dmmsf} = 100\ (Btu/lb\text{-}40S)}{(100\text{-}1.10A\text{-}S}}$$

2) $$\mathbf{\frac{VM_{dmmsf} = 100\ (VM\text{-}0.1A\text{-}\ S)}{100\text{-}\ 1.10A\text{-}S}}$$

Where:

S=Sulphur

A=Ash

The generalised correction for sulphur provided by Suggate (1959) was used for VM and CV. This was due to limited information being available of the relative percentages of organic, pyritic and sulphate sulphur. In cases where this information was available, calculations indicated the sulphur was primarily organic, with pyritic sulphur and sulphate sulphur at subsidiary levels.

Suggate (1959) recommends a correction factor of 1.10 for VM based on an average of New Zealand coalfields. This has been used in this study, as a specific value has not been developed for the Kaitangata Coalfield.

2.4.2.4 Laboratory Error

Error associated with techniques from laboratory methods have been estimated using the ASTM D 5865 (ASTM, 2002) reproducibility guidelines. Error limits associated with the precision of testing are compared between two different laboratories doing the same techniques on the same sample. This is necessary as it is very rare that samples are cross-checked between laboratories (Speight 1983). The error limits accepted for this study are therefore ±164 Btu/lb (dry basis).

2.4.3 Suggate Rank Plots

Suggate plots have been used in this study as a rank indicator that compares CV (Btu/lb) with VM. Suggate Rank has also been used to note perhydrous coals (coals that plot above the New Zealand Coal Band) and also as an indicator of coal type variations (Suggate, 2000).

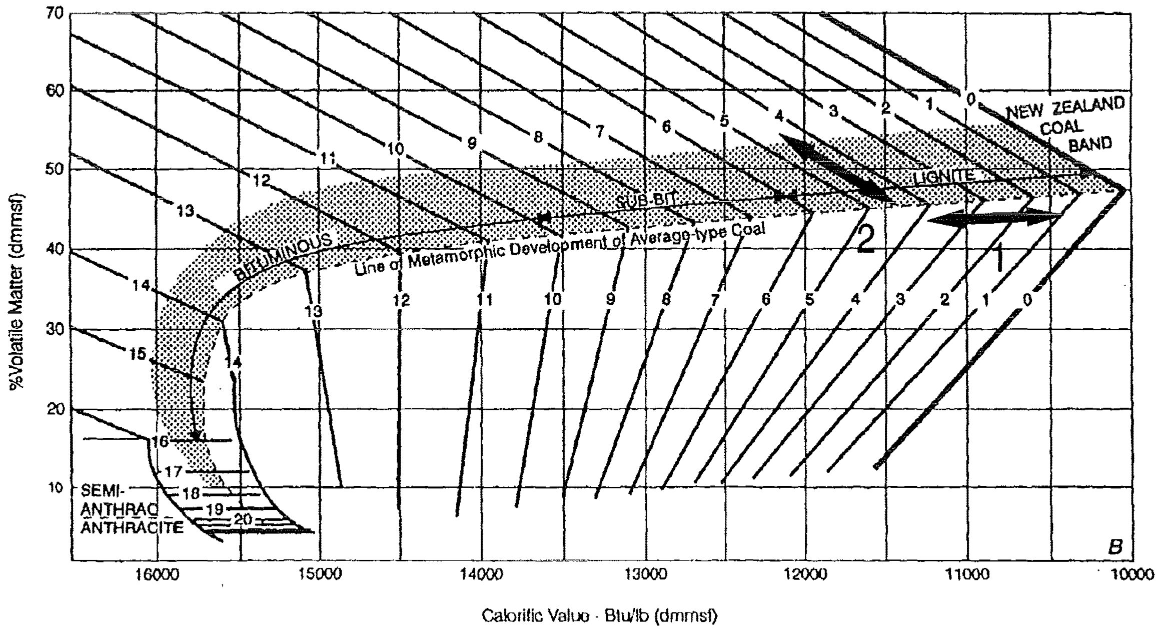
Suggate (1959) studied the progressive rank changes in New Zealand Late Cretaceous and Cenozoic coals during coalification and related changes in coal rank to variations in geological history (Suggate, 2000). This was developed into the Suggate Rank Scale, which allowed the development of a line of coalification relating to New Zealand coals. The result of this study, and further work in the 1980's, was the development of a line of average coal type. This was done by comparing the average of high hydrogen coal types from New Zealand with lower hydrogen coals from Australia, and from the Northern Hemisphere to develop the average coal band (Suggate 2000). The differences between coal type and coal rank are demonstrated in Figure 2.7. Rank refers to an increase in coalification (indicated by the number 1) increasing progressively to the left. Coal type refers to variations in the coals constituents due to plant type prior to burial, or changes during early peatification or coalification (indicated by number 2).

2.4.3.1 Suggate Rank and Ash Content

The CV and VM corrections mentioned in section 2.4.2.3 are applied to all coal samples used in this study. Once coals are corrected to this basis, they are analysed for their ash content before being plotted on Suggate Rank plots.

Preliminary analyses in this study found that ash values in excess of 11% caused variation in Suggate rank which was not purely the result of rank. Such errors were minimised by selecting low ash coal plies for representing coal rank in various seams. However, this was not always possible due to limitations of the data set. Therefore, samples with ash values in excess of 11% are plotted with an asterix next to the drillhole name on Suggate plots. Ash related perturbations in rank are not as such that they would cause major variance in rank, although it is important to minimise error influences on data such as those created by high ash content.

By using Suggate Rank as an analytical method, it is hoped that the application of coal chemistry analyses on Kaitangata coals is more tailored to rank specifications of New Zealand coals.



The Rank(S) classification, with the New Zealand Coal Band superimposed (Suggate 1959): A, C-H axes; B, CV-VM axes. The ASTM rank ranges (ASTM 1993), which have been added, can be applied only approximately, but provide useful general terms indicating rank increase. The coalification path of Average-type Coal is based on all coals, not solely New Zealand coals.

Figure 2.7: Suggate Rank classification modified from Suggate (2000).Note: 1 refers to rank variation in coals. Whereas, 2 refers to type variation in coals.

CHAPTER THREE

STRATIGRAPHY

3.1 INTRODUCTION

The stratigraphy of the Kaitangata Coalfield is complex, primarily due to Tertiary deformation and faulting, but also to the repetitive nature of the Taratu Formation which comprises the majority of the coalfields stratigraphy, including all coal bearing strata. The Taratu Formation consists of interbedded conglomerates, sandstones mudstones and coal which can be divided into three broad groups of members, the Lower, Middle and Upper Taratu Members, each of which relate to different phases of basin development.

Firstly, the purpose of this chapter is to delineate the stratigraphy of the Kaitangata Coalfield and outline contributions made by previous authors. Secondly, this chapter will discuss stratigraphic analyses completed in this thesis in which cross-sections and coal isopach maps have been used to interpret lithostratigraphic relationships and depositional history.

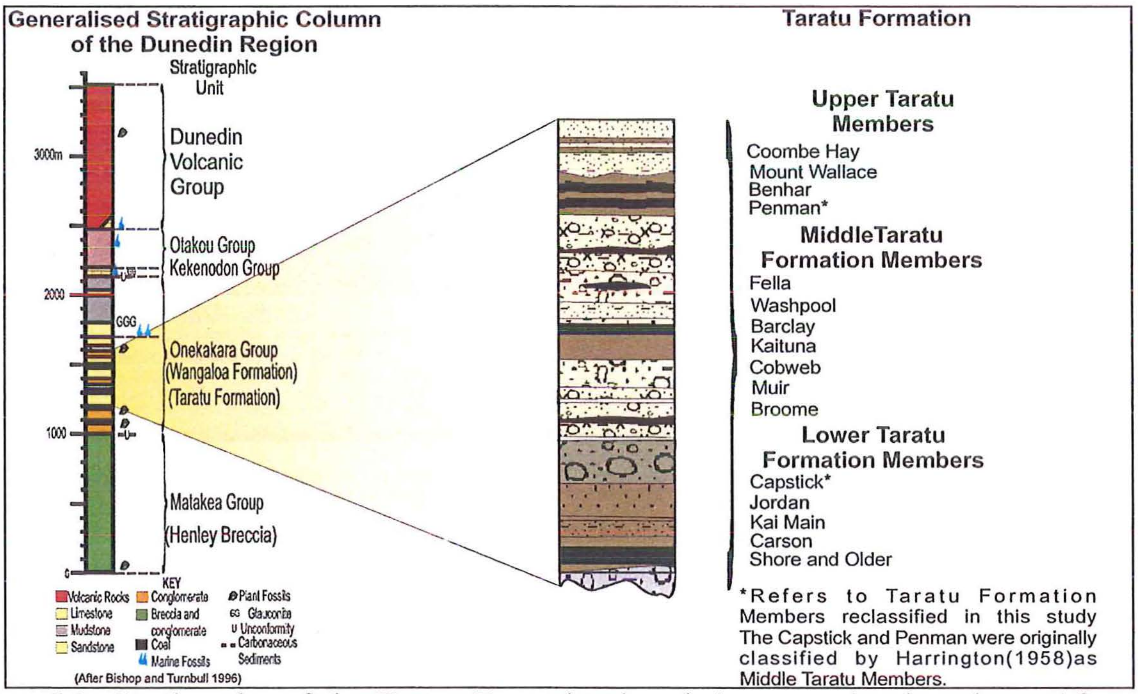


Figure 3.1: Stratigraphy of the Taratu Formation in relation to regional geology. After (Bishop and Turnbull, 1996).

3.2 STRATIGRAPHIC OVERVIEW

3.2.1 Caples Group (Basement)

Basement in the Kaitangata Coalfield is comprised of non-schistose greywacke (litharenites) belonging to the Caples Group. This has previously referred to as the Tuapeka Group by other workers in the Kaitangata Coalfield, as originally named by Marshall (1918). However, as the result of extensive study on lateral equivalents of the Textural Zone I (TZ I) of the Caples Group (approximately 100km NW of the Kaitangata Coalfield) the use of the Tuapeka Group has largely been abandoned (Bishop and Turnbull, 1996).

The Caples Group is thought to be Permian-Triassic in age (Bishop and Turnbull, 1996) and to have undergone metamorphism during the early Mesozoic. Changes in the type of metamorphism from non-schistose to schistose textural zones have been mapped across the Caples Group. In these rocks, metamorphic grade increases to the north and northeast of the Kaitangata Coalfield. Caples Group has not been intersected in the Kaitangata Sector of the coalfield. However, the blue-green grey sandstones of the Caples Group are evident in parts of the Benhar Sector and is currently quarried near the Balclutha township (Duff and Barry, 1989).

3.2.2 Henley Breccia

The Henley Breccia unconformably overlies the Caples Group. Due to lack of extensive exposure of this formation, and the unknown nature of its relationship below the Taratu Formation in the Kaitangata Coalfield, the exposures on the Mount Misery dome and at the type section in the Tokomairiro Gorge in the northeastern margin of the Kaitangata Coalfield are used to describe this stratigraphic unit. A rough age of the basal Henley Breccia is given by Couper (1958) as no older than Albian. This is based on the presence of angiosperm leaves in concretions (Harrington 1958).

Ongley (1939) mapped the type section of the Henley Breccia in the Tokomairiro Gorge, which borders the Kaitangata Coalfield, and concluded that the Henley Breccia was in excess of 1000m and coarsening upwards from carbonaceous siltstone and mudstone into sub-schistose greywacke clast conglomerates and breccias interbedded with red bands and blue-grey sandy lenses. Ongley (1939) then noted that these are succeeded by grey and pink boulder and block fanglomerates which vary in size up to block size. Although the exposure of the Henley Breccia is limited in the Kaitangata Coalfield, erosive remnants have been mapped by Harrington (1958) on the Mount Misery Dome, and on the western slopes of Saddle Hill. The depositional environment for the Henley Breccia is described by Harrington (1958) as localised alluvial fans at the foot of fault margins.

Imbrication of clasts within the breccia suggest a southwest paleoflow direction, with clasts becoming more angular and larger in northwest and westerly directions. In most places the Henley Breccia dips 14-30° west to north-west (Bishop and Turnbull, 1996), however approaching the Kaitangata Coalfield the dip is variable with lower beds dipping at 14° and the upper beds dipping at 40° both trending northwest (Harrington,1958). The provenance of the Henley Breccia varies along the strike of various faults, the sediment eroded from individual fault scarps usually represents the erosion of the metamorphic grade of Caples Terrane in that area (Bishop and Turnbull, 1996).

3.2.3 Taratu Formation

The nature of the contact between the Henley Breccia and the overlying Taratu Formation is largely unknown. It is assumed to be unconformable due to the difference in bedding orientation which indicates tilting of Henley Breccia beds prior to the deposition of the overlying Taratu Formation (Harrington, 1958).

The Taratu Formation is a complex sequence of coal measures interbedded with carbonaceous mudstone and sandstone, truncated by thick conglomerates often eroding earlier deposits (Ongley, 1939; Harrington, 1958; Raymond, 1985; Duff and Barry, 1985; Sherwood, *et al.* 1992).

The Lower Taratu Formation is comprised of conglomerates interbedded with mudstones, sandstones and thick coal seams which thin rapidly to the northeast. Conglomerates are typically clast supported, although there is a high percentage of coarse, angular greywacke sand matrix. Clasts are typically well rounded with pebbles and cobbles varying from 7cm-15cm (Harrington, 1958).

The Middle Members are generally less coarse and are often composed of quartz granules (referred to as 'grit' by previous authors) with a quartz sand or clay matrix. This is distinctly different in composition from the Lower Members apart from where Middle Members onlap onto basement highs where there is a local greywacke signature in the quartz dominated conglomerates (Harrington, 1958).

The Upper Taratu Members have a wider geographic extent than the Lower and Middle Members. They exclusively occupy the Benhar Sector as well as occur as erosive remnants in the Kaitangata Sector, whereas, the Middle and Lower Taratu Member are restricted in distribution to the Kaitangata Sector. The Upper Taratu Members show a close resemblance to the Middle Taratu Members being composed of quartz conglomerates, sandstones, and interbedded mudstones and coals. McClelland (1984) notes that facies in the north of the Benhar Sector are coarse but their lateral equivalents in the southern Benhar Sector are fine mudstones, siltstones with minor conglomerates.

3.2.4 Wangaloa Formation

The Wangaloa Formation is part of the Onekakara Group and is regarded as Paleocene-late Eocene in age (Bishop and Turnbull, 1996). The Wangaloa Formation was named by Marshall (1917) describing the fossiliferous beds that stratigraphically overlie the Taratu Formation (Ongley 1939). Although, only erosive remnants of this relationship exist in parts of the Benhar Sector, the most inland parts of the Kaitangata Sector and the coastal section to the far east of the Kaitangata Sector (Ongley, 1939; Harrington, 1958; Barry, 1985). Lindqvist and Douglas (1987) suggest an interfingering relationship between the Wangaloa Formation with the upper five Taratu Members until the Wangaloa Formation dominated deposition in the Early Paleocene.

3.2.5 Dunedin Volcanic Group

The Dunedin Volcanic Group refers to a series of volcanic events which occurred between 21-10 Ma in the Middle-Late Miocene (Coombs, *et al.*1986). This included both the main eruptive event of the Dunedin volcano (13-10 Ma), and also many older intrusives (up to 21 Ma) both northwest and southwest of the Dunedin Volcanic Centre (Sewell and Weaver, 1989). The intrusives to the southwest extensively intruded the Taratu Formation conglomerates north of Milton. Such intrusives have also been intersected in several underground mines in the Kaitangata Sector (Ongley, 1939; Harrington, 1958). In the Barclay Mine at Taratu Mine in the Kaitangata Sector, basaltic dykes have been intersected during mining. Dykes have been observed to intrude along faults with several meters of throw. For example, a dolerite dike at least 10 meters wide and 370 meters long with a few feet of throw was traced through the Taratu mine. A similar dyke can also been seen near the Sunnyvale Mines working the same seam to the southeast of the Taratu Mine, although no information exists on this intrusive (Duff, 1985; Bishop and Turnbull, 1996).

3.3 STRATIGRAPHIC ANALYSIS OF THE TARATU FORMATION

3.3.1 Previous work on the Taratu Formation

Harrington (1958) conducted the most extensive mapping of the Kaitangata Coalfield and classified the Taratu Formation primarily on basis of areal extent (Raymond, 1985). This can be seen in Harrington's (1958) classification of the Lower Taratu Members: "The beds below the Capstick Coal Horizon do not crop out at the surface, being mainly below sea level, and it is convenient to call them the lower members of the Taratu Formation". Harrington's (1958) division of the Taratu Formation comprised 17 coal bearing members (Figure 3.1), although the Redfoot Member has been removed, upon investigations by McClelland (1984) who correlated it laterally with the Mount Wallace Member. Members of the Taratu Formation are recognised by the presence of laterally and vertically extensive conglomeratic packages which bind fine grained facies into groups (Harrington, 1958; Duff and Barry, 1985; Raymond, 1985).

Although many researchers in the Kaitangata Coalfield since Harrington (1958) agree with his mapping and lithological divisions (McClelland, 1984; Duff and Barry, 1985; Raymond, 1985; Barry, 1985; Browne, 1986; Lindqvist and Douglas 1987), Duff (1985) notes that there are problems with the lateral continuity of Harrington's (1958) lithological members. Duff (1985) regards this as primarily due to lateral facies changes.

Table 3.1: Classification of Taratu Formation Members

Harrington (1958)	McClelland (1984)	Lomas (This study)
UPPER TARATU MEMBERS Coombe Hay Mount Wallace Redfoot Benhar Main	**UPPER TARATU MEMBERS** Coombe Hay Mount Wallace Benhar Main	**UPPER TARATU MEMBERS** Coombe Hay Mount Wallace Benhar Main Penman
MIDDLE TARATU MEMBERS Penman Fella Washpool Barclay Kaituna Muir Cobweb Muir Broome Capstick	**MIDDLE TARATU MEMBERS** Penman Fella Washpool Barclay Kaituna Muir Cobweb Muir Broome Capstick	**MIDDLE TARATU MEMBERS** Fella Washpool Barclay Kaituna Muir Cobweb Muir Broome
LOWER TARATU MEMBERS Jordan Kai Main Jordan Carson Shore	**LOWER TARATU MEMBERS** Jordan Kai Main Jordan Carson Shore	**LOWER TARATU MEMBERS** Capstick Jordan Kai Main Jordan Carson Shore

The classification by Harrington (1958) of Taratu Members, does not allow for lateral variation in the depositional setting. However, Ongley (1939), and later Harrington (1958), performed detailed mapping on the Kaitangata area which recognised several factors which they believed were diagnostic for some sequences. Ongley (1939) commented on the upward decrease in greywacke component in clastic units, and Harrington (1958) further noted that there was a significant change from greywacke to quartz dominated conglomerates after the deposition of the Broome Member.

Harrington (1958), McClelland (1984), Duff and Barry (1985), Raymond (1985), and Browne (1986) have all performed stratigraphic correlations of the coalfield. Harrington (1958) had the benefit of extensive underground mines in the Kaitangata Sector to assist with lateral correlation, and used the extensively mined Kai Main seam as a datum. This allowed for identification of significant detail in assessment and mapping faults in the southern portion of the Kaitangata Sector. Harrington's (1958) correlations drew him to the conclusion that the depositional setting of the Taratu Formation was "a series of peat swamps and coalescing floodplain deposits in a structural depression". This broad idea has not been altered significantly but has received some refinement due to analyses completed in the mid to late 1980's from the following people; McClelland (1984), Duff and Barry (1985), Raymond (1985), Browne (1986), Lindqvist and Douglas (1987), Browne and MacKinnon (1989) and Duff and Barry (1989). This extensive, short period of analysis was initiated by the NZCRS.

McClelland (1984) provides an analysis of Taratu Members, noting specifically the high sulphur nature of the Barclay and Kaituna Members and the location of channels in the Benhar Sector. McClelland (1984) suggests a depositional environment of low lying interconnected lakes or peatbogs for the Kaituna and Barclay Members. The high sulphur content was the result of either tectonic subsidence, allowing the introduction of marine waters, or a eustatic sealevel rise. McClelland (1984) further adds that there is no evidence of a beach or offshore sands nor marine fossils within five kilometres of the Members. However, Duff and Barry (1985) note the predominance of laterally correlative sands, which they have interpreted as barrier bar deposits.

Raymond (1985) concentrated primarily on the depositional environment of the Upper Taratu Members, focusing on the Benhar Sector of the coalfield, and to the north of the Kaitangata Sector in the area surrounding the Elliotvale opencast mine. Raymond (1985) completed some stratigraphic cross-sections although these primarily concentrated on the Benhar Member, in order to assist sampling for coal petrologic samples. Lithofacie and coal maps were also completed by Raymond (1985) for the Benhar Sector of the coalfield. Raymond's (1985) lithofacies analysis primarily used maceral assemblage and microlithotype of the coals, although he did complete analysis on sediment distribution and composition. He concluded that the coal type changed between the Lower and Upper Benhar Sector, from coals deposited in limnotelmatic swamps (lakes with trees and shrubs), to coals deposited in swamps that were more telmatic (reed dominated). However, the Mount Wallace peat bogs were considerably drier with a higher hypautocthonous/allocthonous peat component of oxidised material in the peat swamp. This oxidised peat and detrital component is confirmed by observations in this study. Raymond (1985) also noted the presence of glauconite and calcareous cement in mudstone and sandstone associated with the coal horizons which he attributed to a marine influence via estuaries during the Upper Benhar and Mount Wallace seam deposition. Raymond (1985) attributed controls on the deposition to localised tectonics allowing the deposition of the peat, and extrabasinal influence affecting sediment influx.

Duff and Barry (1985) did numerous correlations of the Kaitangata Coalfield, and agreed with Harrington's (1958) stratigraphy. However, they noted that Harrington's (1958) use of the Kai Main seam as a datum could not be used basin wide due to washouts, lateral facies changes and vertical similarity in fine-grained packages. From several seismic lines completed during the Stage Three New Zealand Coal Resources Survey, Duff (1985) concurred that faulting was much more pronounced than previously thought. Duff (1985) also warned that some correlations completed during this programme were tentative due to the unknown effect of normal and reverse faults. Duff (1985) provided some excellent stratigraphic correlations, also noting the presence of the Summer Hill and Castle Hill paleochannels across the Castle Hill Fault. In addition, he suggested the presence of a northerly paleochannel, which was identified in this study and called the Kai Point paleochannel. Duff (1985) described the depositional setting for Taratu Formation as sediment fed from paleochannels relating to the erosion of a hinterland behind the Benhar Sector; once this source was exhausted, the provenance became primarily dominated by the quartz component sourced via braided rivers from another area. Duff (1985) also noted the vertical and lateral increase of organic sulphur in the Middle Members, which he related to marine incursions into the peat bogs.

Lindqvist and Douglas (1987) suggest that deposits from paleochannels to the north do not have braided river structures, but instead have features of meandering rivers. This is based on the presence of epsilon cross-stratification above the highwall of the Barclay seam in the Kai Point opencast mine, the Wangaloa Mine and along the coastal section of Coal points and Wangaloa Domain. Lindqvist and Douglas (1987) suggest the depositional environment was a series of high sinuosity meander belts that down cut and significantly eroded into peats.

Browne (1986) and Browne and MacKinnon (1989) used palynostratigraphy to try to overcome lateral correlation problems across the coalfield. Browne (1986) disputed Duff and Barry's (1985) stratigraphic correlations. However, problems using pollen as a proxy for depth resulted in Crouch (1994) to conclude that Browne (1986) and Browne and MacKinnon's (1989) depiction of palynostratigraphy was incorrect. This study agrees with Crouch (1994) and regards Duff and Barry's (1985) cross-sections as the more correct lateral correlation and stratigraphy. Despite problems with palynostratigraphy, Browne's (1986) thesis provided some important information relating to the depositional environment of the Taratu Formation identifying the dinoflagellate species *Isabelidinium drugii* and *I. seelandicum*. These are not only indicative of a marine influence in the coalfield at the time of deposition, but also provide biostratigraphic dates confirming the coals at this depth were latest Cretaceous in age.

Other authors have noted the presence of biostratigaphic indicators such as trace fossils. Barry (1985) interpreted the coastal section the coast to the far east of the Kaitangata Sector near the Wangaloa Domain, observing the presence of the ichnogenus *Rhizocoralluim* and the ichnogenera *Ophiomorpha* or *Thellassinoides* in what he interprets to be the basal Coombe Hay Member, based on Harrington's (1958) mapping. The presence of these trace fossils are indicators of an estuarine environment which Barry (1985) suggests was an almost continuous sequence from the Taratu Formation to the overlying Wangaloa Formation. This section has also been studied by Lindqvist and Douglas (1987) who confirm the presence of low diversity trace fossils such as *Skolithos* in the basal Washpool Member. A detailed study confirming the continuity of the beach section has not been completed.

3.4 STRATIGRAPHIC ANALYSIS IN THIS THESIS

In order to interpret the basin history and detail the coal and clastic facie distribution for rank assessment the following objectives were used:

1) To interpret the relationship between the Castle Hill Fault and depositional facies in the coalfield,
2) Better understand the stratigraphic relationship between Taratu Formation members in the coalfield,
3) Delineate lateral seam continuity (and thickness), as well as assess mechanisms controlling seam distribution,
4) Develop an interpreted depositional environment for the Kaitangata Coalfield.

Cross-sections A-F (see back pocket of thesis) were produced to show lateral and vertical relationships between the coal measures. This was done by correlating lithological patterns of depositional facies in laterally consecutive drillholes. The stratigraphy of the Kaitangata Sector has a high rate of lateral variation and the problem of using a singular datum, as mentioned by Harrington (1958) and Duff (1985) was soon realised. This study concluded that it is impossible to use a single datum in the Kaitangata Sector, and multiple seams were used depending on the area of the basin being interpreted. Initially correlations used in this study were purely lithostratigraphic, to remove any bias created by placing names on depositional intervals. However, once familiarity with stratigraphy was established, the Kai Main coal horizon was commonly used as a datum for the Lower Members and the Barclay for the Middle Members and the Benhar Main coal horizon, as these were the most laterally extensive coal seams available.

Coal and conglomerate isopach thickness maps were created by using the downhole thickness of coal and carbonaceous mudstone bearing strata encounted in drillholes across the basin. This was then correlated to different coal-bearing Members.

3.4.1 Revision of Stratigraphy

This study mostly agrees with Harrington's (1958) classification of the Taratu Formation Members, although it favours McClelland's (1984) deletion of the Redfoot Member and prefers to reclassify some of the Middle Taratu Members. Harrington's (1958) Capstick Member (previously a Middle Taratu Member) is designated to the Lower Taratu Members in this study, and the Penman Member (previously a Middle Taratu Member) to the Upper Taratu Members (Table 3.1). Reclassification was decided after the Capstick showed a greater affinity to the Lower Members based on lithostratigraphic conglomerate composition. This was later reinforced by coal chemistry (rank details in Chapter Four).

The Penman Member was reclassified based on the basin development and geological history. The Upper Taratu Members refer to the Members which formed when the Kaitangata Coalfield's basin extent widened to include the Benhar Sector as depositional basin during the latest Cretaceous-early Paleocene. When the Castle Hill Fault scarp was overtopped during early Penman times with a more regional framework controlling deposition. The fact that the Penman Member was the first established coal member on the Benhar paleohigh inherently relates it to this new stage of basin development, and has prompted the reclassification of this member to the Upper Taratu Members in this study.

3.4.2 Lower Taratu Members

The Lower Taratu Members are composed almost exclusively of greywacke (litharenite) conglomerates with only a minor quartz component, mudstones, angular sandstones and low sulphur coals (0.5-1.5 %).

Coal horizons show the following patterns; vertically, coal thickness varies from <1m to in excess of 15m. Coals are commonly interbedded with mudstones, and occasionally, with sandstones and conglomerates. The upper limit of coal horizons are often eroded and truncated by conglomerates, which can reach 70m in thickness. Laterally, coals either terminate against, or split and interfinger with conglomerates. In cross-section C-C' both of these relationships can be identified (Appendix A). Between drillholes 5268 and 5270, the Kai Main seam changes from a thickness of 3m in drillhole 5268, to be completely absent in drillholes 5270 and 3063. Instead, it is replaced by conglomerates that are up to 50 meters thick, which are then succeeded by a fining sequence of greywacke dominated sandstones and mudstones. A general interfingering relationship can also be observed between coal and conglomerate facies approaching drillhole 5270, where coal horizons thin and are often truncated by conglomerates that increase in thickness towards drillhole 3063.

The thickest coal deposits in the Lower Taratu Members occur in a generally north-south trending belt, approximately 1.5 km from the Castle Hill Fault margin. However, the depocenters where maximum coal accumulation occurred changed over time for the successive coal-bearing members, although, throughout the Lower Members a persistent depocenter developed near drillholes 5258, and to the southeast near the drillhole cluster surrounding 5051-5053 (Figures 3.2, 3.3 and Appendix B).

Conglomerates in the Lower Taratu Members are primarily composed of local greywacke (litharenites), which vary in angularity and grainsize between subangular to subrounded pebbles and cobbles. These conglomerates are both clast and matrix supported. Clast supported conglomerates are typically massive with no indication of bedding, except where they are succeeded by fining sequences of sandstone and mudstone. Matrix supported conglomerates are very angular but are generally finer than the clast supported conglomerates, varying in size from granules to cobbles, but are typically pebble sized.

A conglomerate percentage isopach map was created by combining the encountered thicknesses of all conglomerates in drillholes for the Lower Taratu Members (Figure 3.4). This showed that conglomerates increase to almost 90% dominance over other lithologies approaching the Castle Hill Fault indicating the presence of a clastic wedge.

The occurrence of laterally eroded coals and the interfingering of coals with clast-supported conglomerates are interpreted to be the result of paleochannels. These paleochannels are prominent features in coal isopach thickness maps where the abrupt absence of coal horizons and the presence of clast-supported conglomerates are interpreted as evidence of channel structures (e.g. Figure 3.2 and 3.3). The activity of the Summer Hill paleochannel can be seen as successive conglomerates interrupting the deposition of many Lower Taratu Member coal horizons. For example, when comparing the Kai Main and Capstick Member coal isopach maps (Figures 3.2 and 3.3), the erosion of the coal horizons in the south during the Kai Main coal horizon has moved more to the southwest in Capstick times. This is interpreted as avulsion of the paleochannel. The fining sequence of sandstones and mudstones, which often overlie conglomerates, is considered to be the result of waning flow conditions after flooding events.

The presence of a clastic wedge, identified by the dominance of conglomerates approaching the Castle Hill Fault margin indicates that the Castle Hill Fault was active during the deposition of the Lower Taratu Members. The interbedded matrix supported, angular conglomerates, are interpreted to be indicative of fault-derived alluvium and is therefore interpreted to be debris flows from the fault scarp.

Alluvial fans are characterised by a rapid reduction in relief at the foot of highlands where sediments accumulate as a fan due to a change in gradient (Einsele, 2000). The conditions necessary to allow the deposition of thick peats on an alluvial fan are typically a shallow basin with high water tables and low gradient (Diesel, 1992). This description can be applied to the Lower Taratu Members, where sediment sourced from hinterlands was deposited in the Kaitangata Sector via paleochannels having lost its transport efficiency upon encountering a lower relief surface, i.e. the downthrown side of the Castle Hill Fault. Sediment was then deposited in a clastic wedge near the fault margin being distributed by channels. These channels avulsed periodically eroding into the peat bogs, which developed on the valley floor due to a high water table. After the stabilisation of channel flow, subsidence resumed in which further peat deposition occurred. Minor flooding and channel avulsions are identified as the interfingering relationship between conglomerates and coals.

Although this is indicative of most relationships seen in cross-section, not all conglomerates in the Lower Taratu Members appear to be derived from extrabasinal paleochannels. Some conglomerates in the Lower Taratu Members show a very local signature, in clast size, angularity and composition and are thus probably sourced directly off the fault scarp from sediment gravity flows, also characteristic of alluvial fan deposits contributing significantly to the thickness of the clastic wedge. This relationship is expressed in a block diagram (Figure 3.5) which show the association between local and paleochannel sourced sediments and peat formation.

An alluvial fan from the Carboniferous of northern Spain, shows many similarities with the Lower Taratu Formation (Figure 3.6). Like the Lower Taratu Members, conglomerates, sandstones, mudstones and coals are deposited on the downthrown fault margin, influenced by paleochannels and fault scarp processes. Heward (1978) describes fans as divided into three areas; proximal, midfan and distal. The proximal fan area is not preserved due to active fan processes. Mid fan areas are composed of either conglomerates or finer fault derived scree (fine breccia). Vegetated areas formed on the abandoned fan surface, with channels occupying active fan segments fed from the fault scarp and extrabasinal channels in which conglomerates and scree deposits are redistributed via channels and gravity flows to mid and distal fan areas. The distal fan area is characterised by fine-grained deposits such as fine sandstones, mudstones and coals. Some rare channel conglomerates exist where active fan lobes and sheet flooding from channels enter these low-lying lake areas Heward (1978). Heward (1978) concludes that the primarily controls on fan processes are the result of tectonic influence and base level changes from neighbouring water bodies. Similar controls on basin development would have existed for the Lower Taratu Members where tectonic movement on the Castle Hill Fault would have undoubtedly affected facies architecture. However, other controls on base level changes such as climatic/seasonal perturbations are speculative and will not be discussed here.

3.4.3 Middle Taratu Formation

The Middle Taratu Members are composed of quartz conglomerates and sandstones, interbedded with mudstones and coal.

During Middle Taratu times, coals typically become more sulphur rich increasing from 0.5-1.5% sulphur in the Lower Members, to between 5-7% sulphur in the Middle Members (Figure 3.9). Middle Taratu Member coals exhibit a similar vertical and lateral facies relationship to the Lower Taratu Members. Vertically, coals are commonly truncated by conglomerates, which are in turn succeeded by a fining sequence of sandstones and mudstones/siltstones. Where conglomerates do not directly overlie coals, thick sequences of carbonaceous mudstones and massive mudstones can occur, these are then overlain by conglomerates. With the exception of the Barclay coal horizon, Middle Taratu Member coals are typically more laterally constrained than the Lower Members and have numerous splits interfingering with conglomerates, also appearing more pod shaped (Figures 3.7 and 3.8).

During the early depositional stages of the Middle Members the sediment type becomes progressively more quartz rich. This begins between the Capstick and Broome Members, with the dominant lithotype being quartz from the Muir Member upwards. Conglomerates are typically much finer than in the Lower Taratu Members, and are primarily subangular to subrounded quartz quartz mostly varying between granule to fine conglomerates in size, with some rarer large well rounded quartz cobbles. A conglomerate percentage isopach map was unable to be completed due to extensive erosion of the Middle Taratu Members on the crest of the Kaitangata anticline. Although, from cross-section A-A' (Appendix A) conglomerates increase in dominance between drillhole 3023 and 3011. Conglomerates in drillhole 3011 show a distinct local signature, being composed of primarily greywacke dominated conglomerates from below 90m. In almost all other drillholes however, quartz conglomerates dominate the Middle Taratu Members.

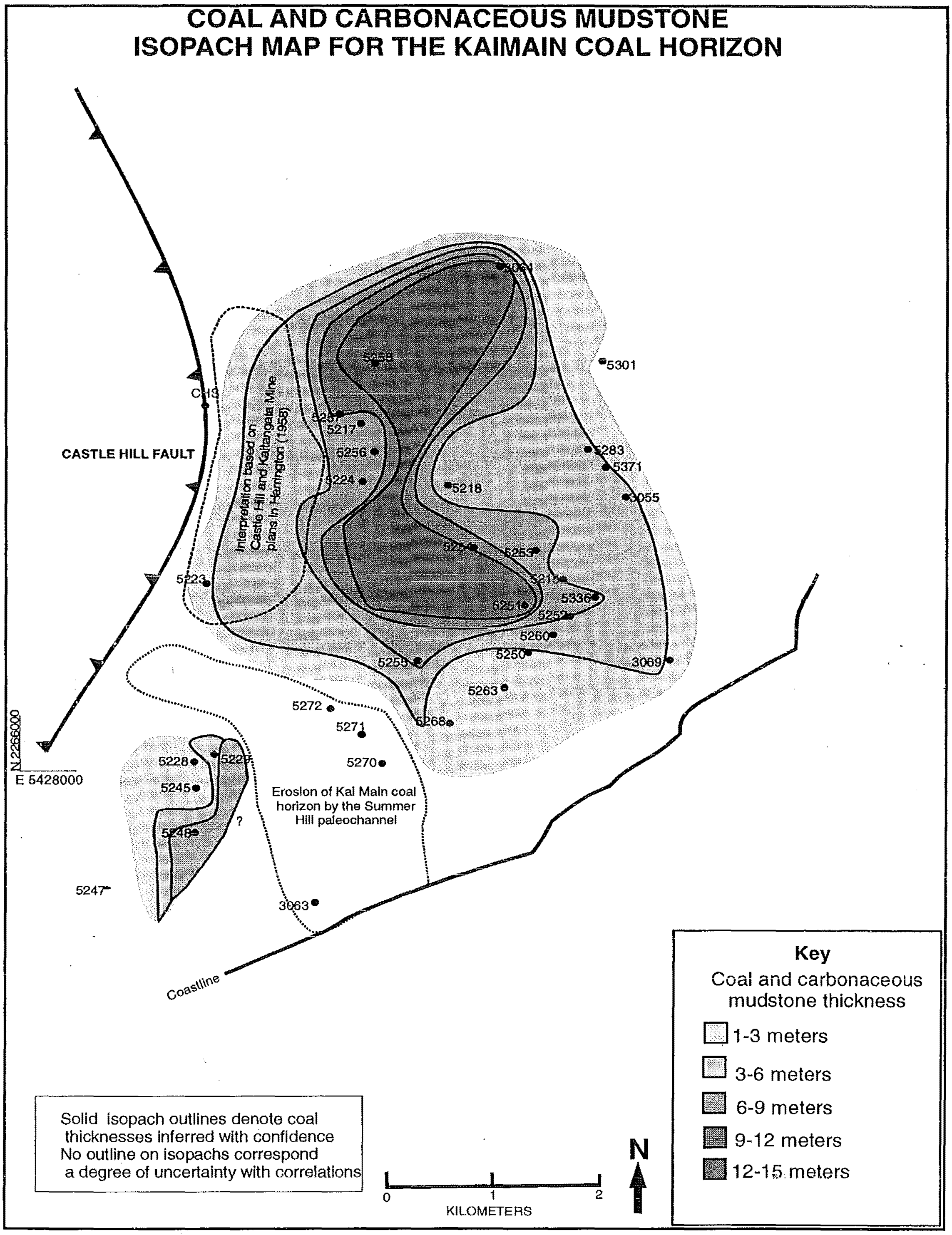


Figure 3.2: Coal isopach map of deposition during the Kai Main Member. Note the absence of coals from Drillholes 5270, 5271. 5272 and 3063. This is due to erosion from the Summer Hill Paleochannel.

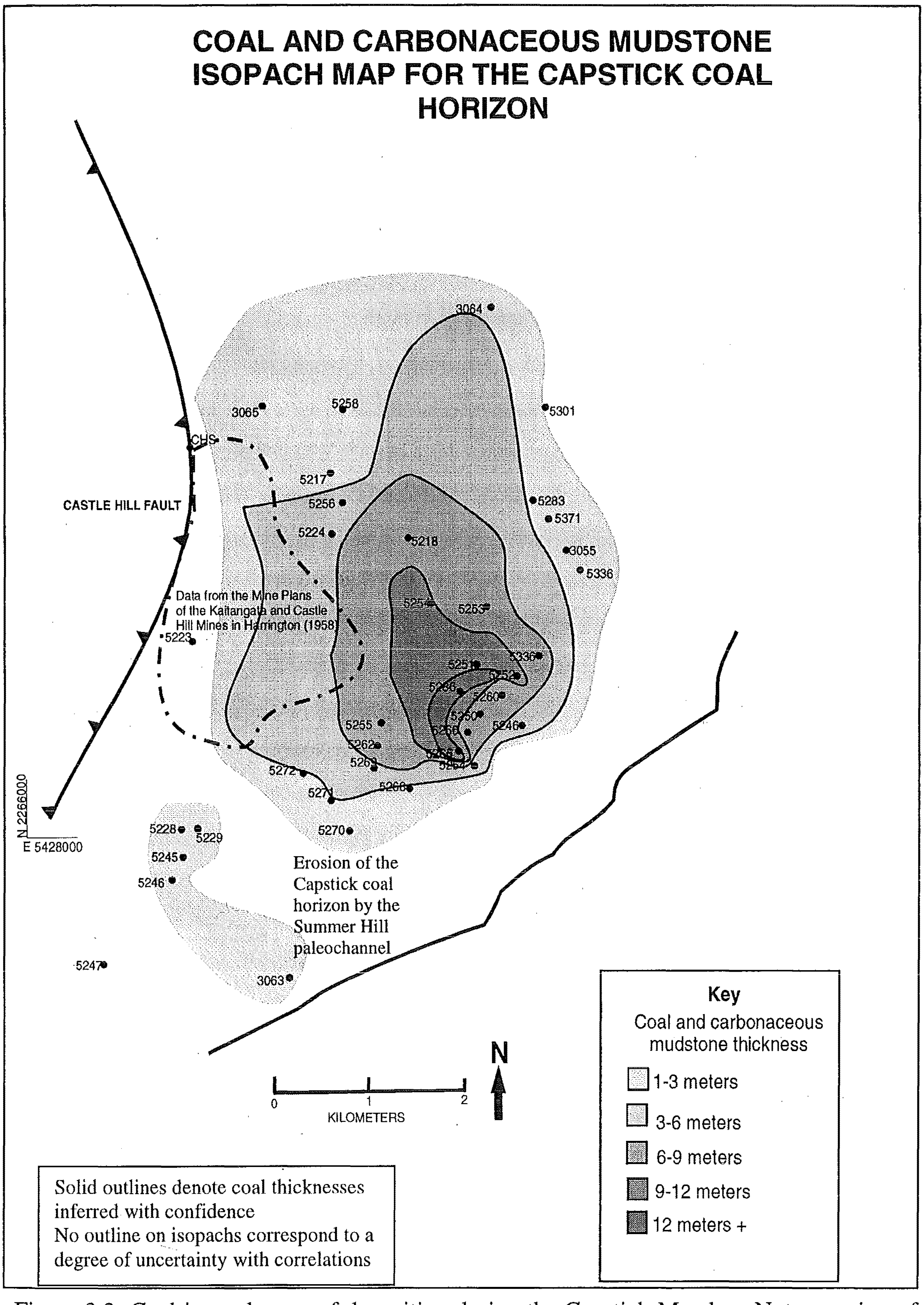


Figure:3.3: Coal isopach map of deposition during the Capstick Member. Note: erosion of the coal measures due to the Summer Hill Paleochannel is slightly different than in Kai Main times. This could possibly be due to river avulsion.

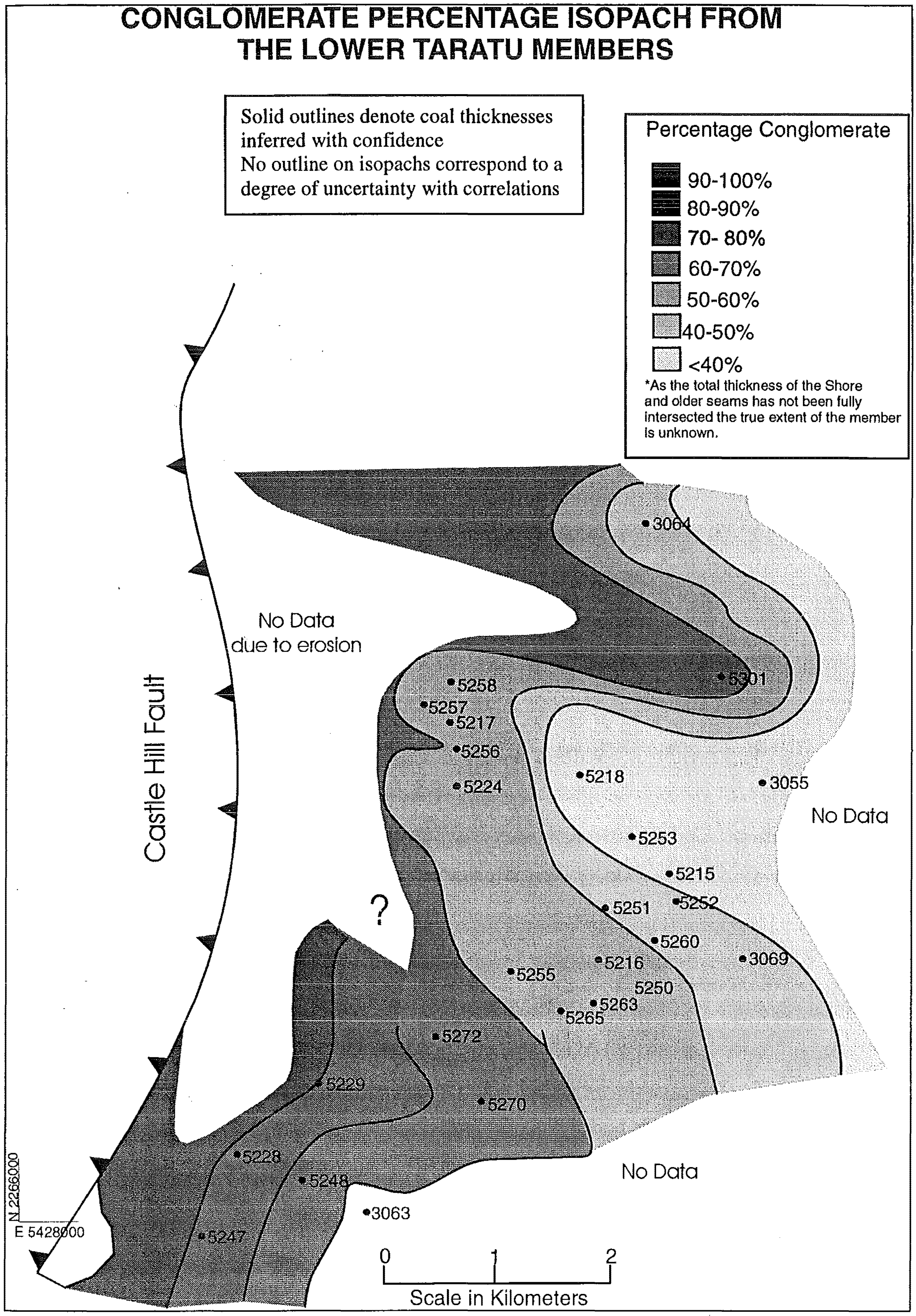


Figure 3.4: Conglomerate percentage isopach map of the Lower Taratu Members.

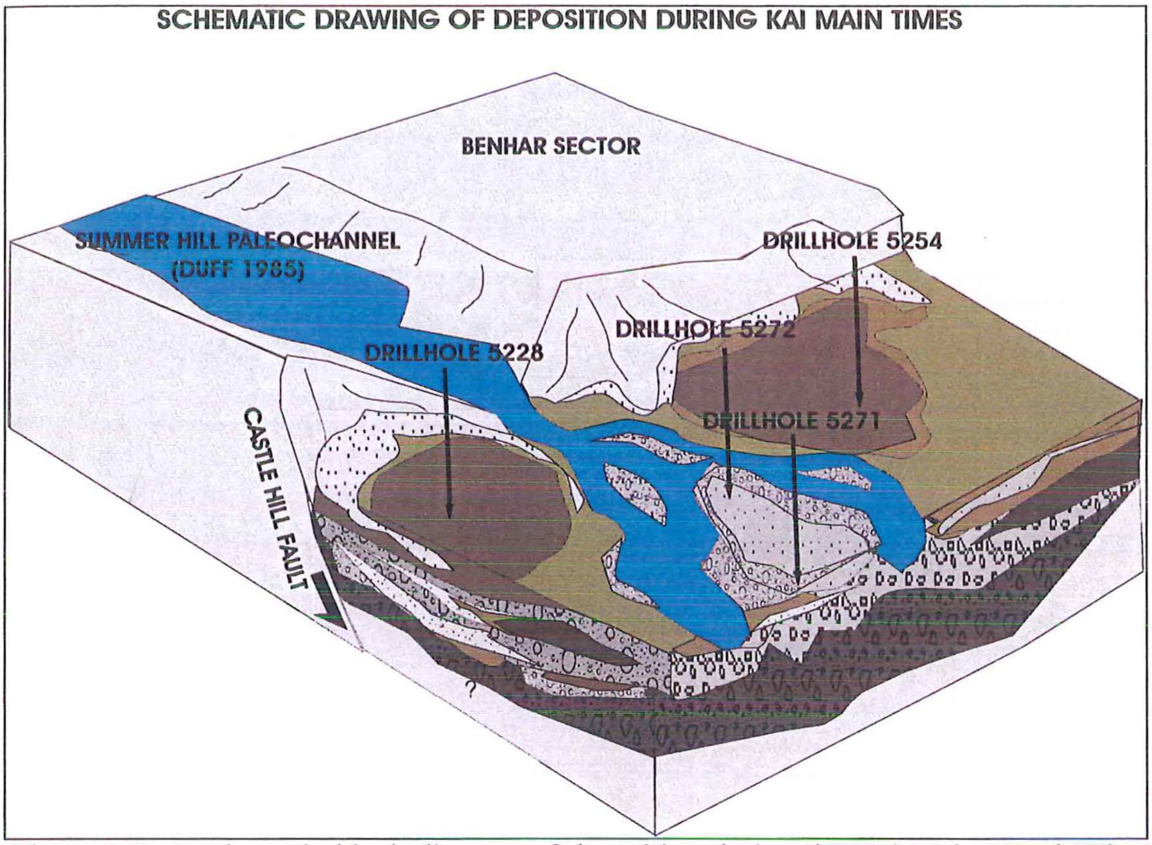


Figure 3.5: A schematic block diagram of deposition during the Kai Main Member in the southern portion of the Kaitangata Coalfield.

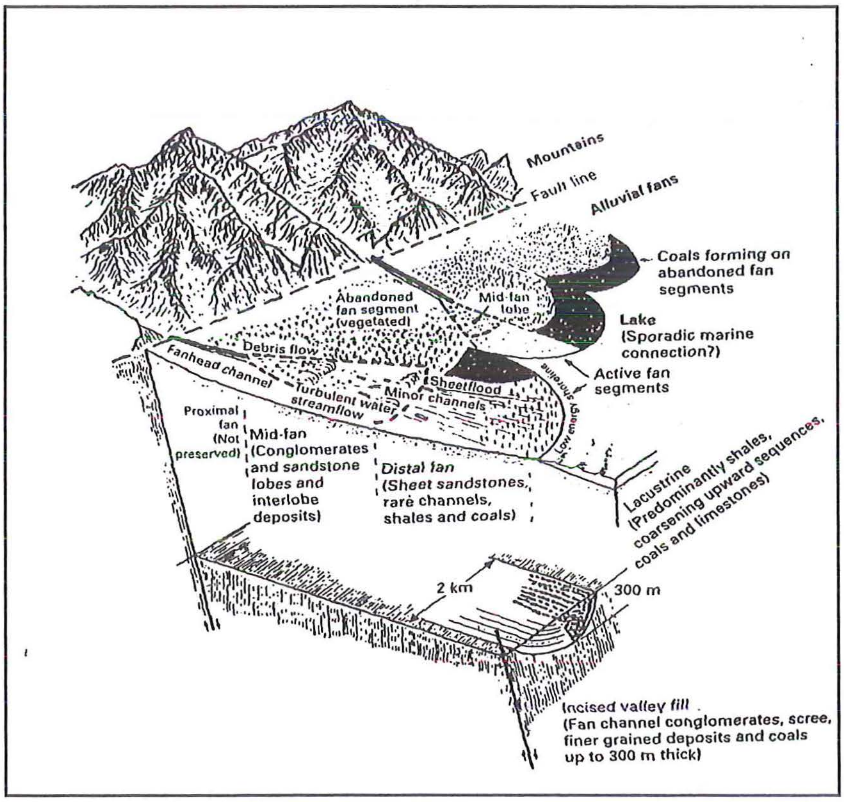


Figure 3.6: Model of a coarse grained, shallow water alluvial fan from the Upper Carboniferous of northern Spain (Heward, 1978).

Lateral facies changes are depicted in cross-section B-B' (Appendix A) where conglomerates associated with the upper Kaituna Member, Barclay and Washpool coal horizons in drillholes 3060 and 3055, grade laterally to interfinger with fine sandstones in drillhole 3043. A similar shift to fine grained lithologies exist in drillholes 3056, 3059, however, coarser quartz gravels predominate to the southwest in drillholes 3041.

Coal Isopach maps show the lateral erosion of coals in elongate structures interpreted to be the presence of paleochannels. These appear to be prominent features in coal isopachs of the Muir Member (Figure 3.7), with the Summer Hill and Castle Hill paleochannels that were previously identified by Duff (1985) active. A new paleochannel, hereby called the Kai Point paleochannel, can be seen to the north of Summer Hill the Castle Hill paleochannels. Another possible paleochannel may exist from the north of the Kaitangata Sector in the Washpool coal horizon (Figure 3.8). With the exception of the Barclay Member (Appendix B.6), coals appear to be more pod shaped with numerous splits. This is probably due to the long-lived presence of paleochannels, which can be seen to be highly erosive in many of the Middle Members (see Appendix B).

Cross-section A-A' shows the influence of the Castle Hill Fault margin on lateral coal formation. It is particularly evident in drillhole 3011, which has no coal measure development at depth compared to more easterly drillholes bearing the lateral equivalents. McClelland (1984) described the sediments in drillhole 3011 are more angular and greywacke rich than lateral equivalents, attributing this to the presence of the Castle Hill Fault scarp. This suggests that the Castle Hill Fault scarp had a limited influence on depositional facies proximal to the fault margin.

High sulphur in coals (organic and pyritic) is thought to be primarily derived from sulphate in seawater (Casegrande, 1987), although there is debate whether sulphur is syndepositional or post depositional (Henderson, 1934; Suggate, 1959; Sykes, 1998). Suggate (1959) discounts the influence of syndepositional marine influence into peatbogs, stating the systematic decrease in sulphur, which is common in New Zealand transgressive coals such as those seen in the Kaitangata Coalfield is due to the downward percolation of overlying marine strata (Suggate, 1959). However, during the deposition of the Barclay Member, elevated sulphur is concurrent with marine dinoflagellates in drillholes 3012, 3013, 3029 and 3036 (Figure 3.10). Dinoflagellates have also been identified by Browne (1986) in the Washpool horizon in drillhole 3028, which also has an elevated sulphur level.

The presence of dinoflagellates and high sulphur is also supported by a lateral facies change to the east which can be seen in cross-section B-B' (Appendix A). This lithological change suggested by Duff and Barry (1985) to be a barrier bar during the deposition of the Barclay Member and is supported by this study, with another possible alternative suggested. Sandstone with fine mudstone as seen in drillholes 3043, 3056 and 3059 could be due to swash bars which can form at the edge of channel mouths accounting for the thick conglomerates (i.e. drillholes 3041) laterally occurring to next to the fine grained mudstone and sandstone near drillhole 3043.

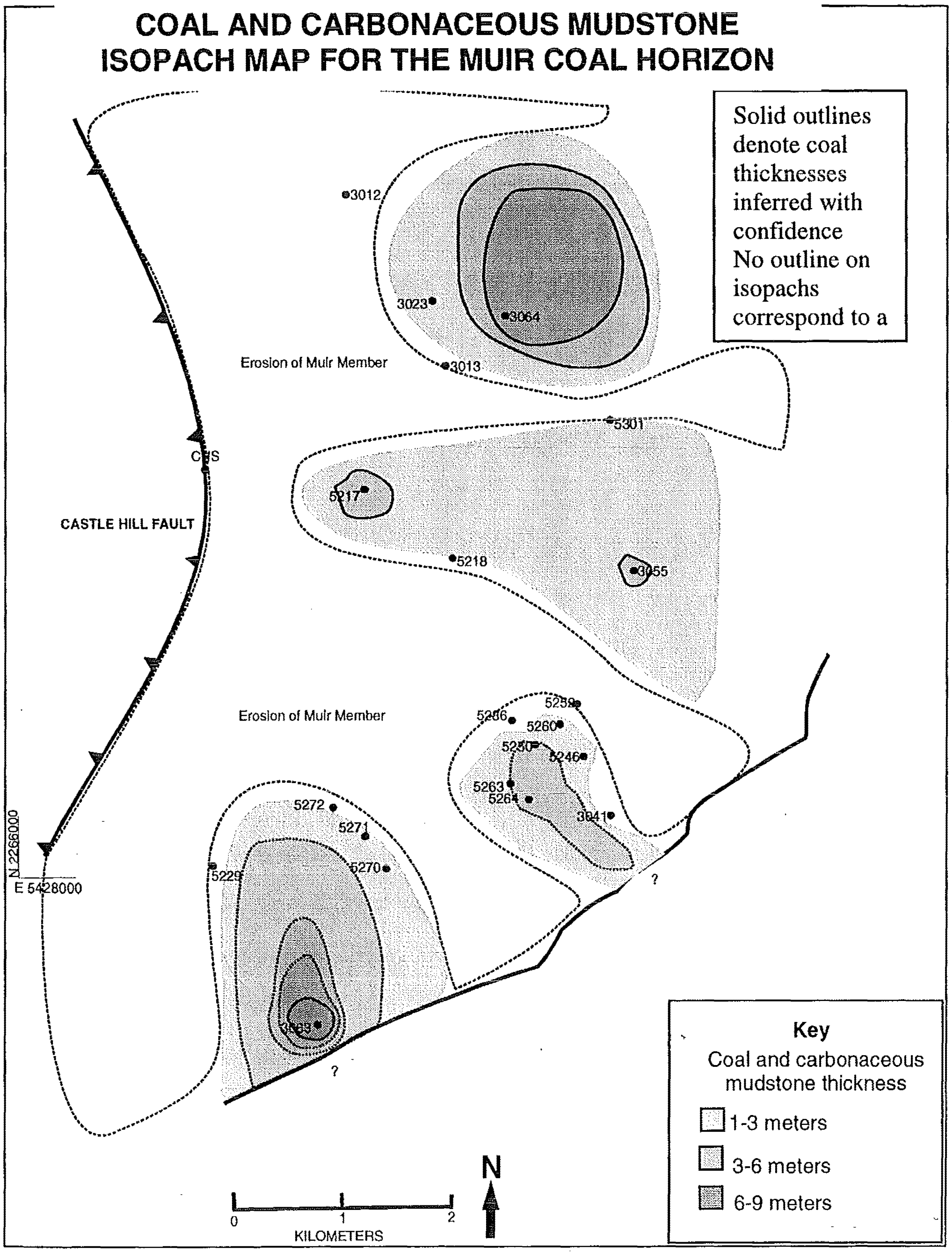


Figure 3.7: Coal Isopach of deposition during the Muir Member times. Note: The existence of multiple paleochannels.

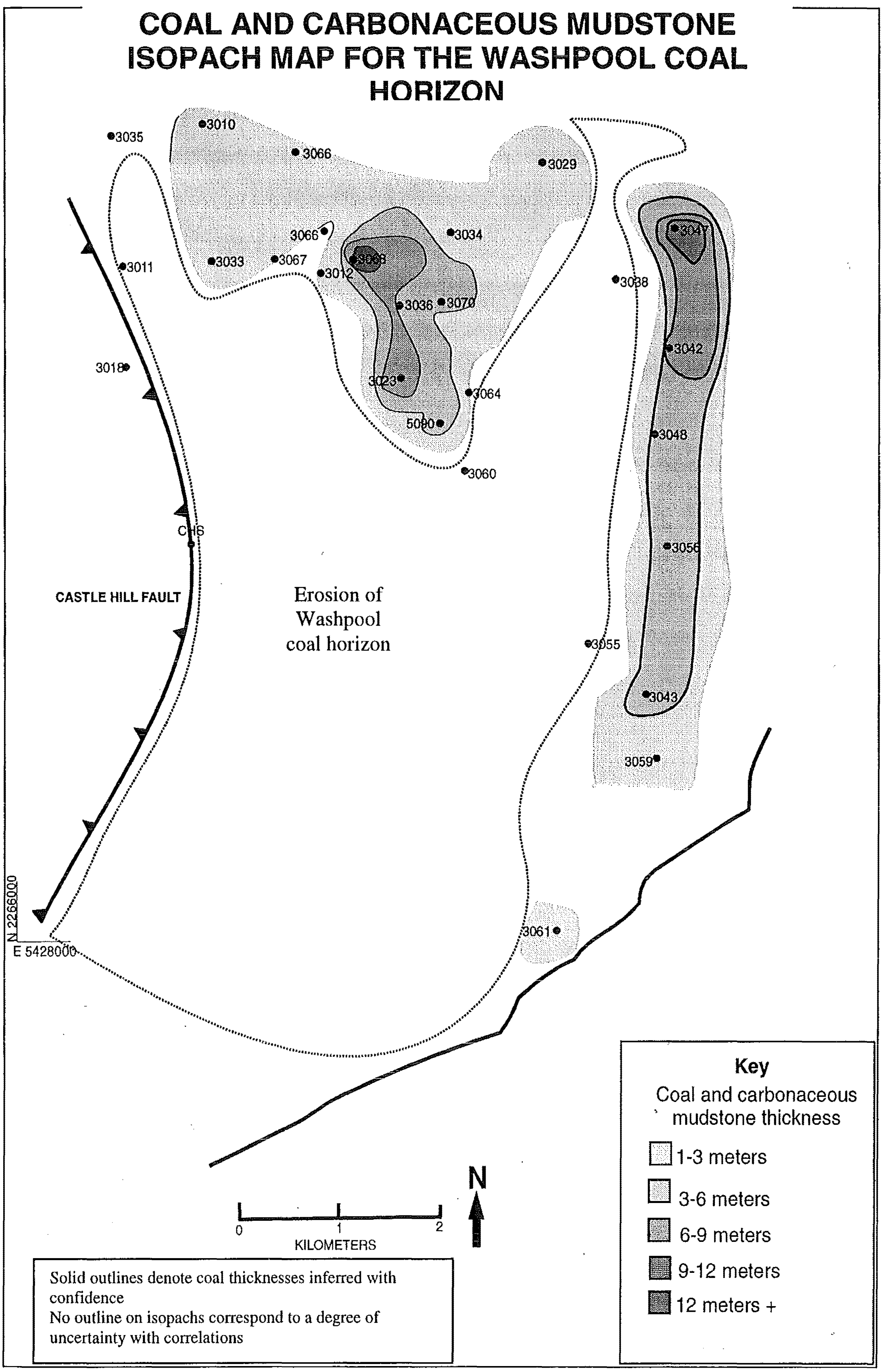


Figure 3.8: Coal isopach of deposition during the Washpool times. Note: Possible erosion of coal measures from a northerly paleochannel.

The depositional environment of the Middle Members appears to have changed considerably from the basin controls affecting the Lower Taratu Formation. This is evident with not only a dramatic shift in the composition of the source material, but there is also a reduction in grainsize in the conglomerates. A change in depositional environment is further supported by an increase in coal sulphur and the presence of dinoflagellates in coal horizons.

The Middle Taratu Formation is interpreted as bridging the stages between the termination of a relatively local alluvial fan system and the beginnings of a more regionally influenced delta plain. During the deposition of the lower Middle Members a transitional period would have occurred in which facies were influenced by both the greywacke and quartz sources which is seen in the conglomerates deposited after the deposition of the Broome Member. During Middle Taratu times paleochannels were relatively well constrained to channel belts although they occasionally overtopped their banks or avulsed into peat bogs. Lindqvist and Douglas (1987) suggested that paleochannels were meandering rivers, rather than braided rivers as suggested by Raymond (1985) and Barry (1985). Assessment of cross-sections and coal isopach maps in this study have noted the relative stability of these paleochannels because of the following factors. Firstly, the presence of paleochannels appears in consecutive coal isopach maps, which indicated they are long-lived. Secondly, for thick coals to be deposited and preserved adjacent to river systems without being eroded during meandering of the river, channels must have been relatively stable for long periods of time. However, this study has not examined channel structures in detail, but it is hereby suggested that rivers may have alternated between meandering and anastamosing types rather than a braided river system. Meandering and anastamosing rivers provide better stability of channels over long periods of time whereas braided rivers would be too active to explain the deposits which exist in the Kaitangata Coalfield (Boggs, 2001). If there was a sea level rise or tectonic subsidence during the deposition of the Middle Taratu Formation river systems would change to adapt to the system change. Such a change could also see a change from meandering to anastamosing rivers during times where there is a lack of coarse clastic material. Some Middle Taratu conglomerates can be seen to have very little structure, apart from faint crossbedding. This is prevalent where thick quartz conglomerates occur. These conglomerates are often have a clay or silty matrix. The effect of such a matrix would provide stability of bank conditions during braided river times, allowing for more stable flow conditions. When flow conditions change, due to changes in the depositional system, e.g. the deltas proximity to its baselevel, either meandering or anastamosing rivers may occur.

Marine incursions are evident in the Barclay and Washpool Members confirmed by the presence of dinoflagellates concurrent with elevated sulphur. This indicates that during the deposition of these coal horizons coal situated at the very limits of the terrestrial system. The laterally correlated sands of the Barclay Member from cross-section B-B' (Appendix A) were interpreted by Duff (1985) as a barrier bar as mentioned previously. These sands probably protected the peats from sustained marine influence, although were breached periodically during highstands or storm activity.

With the exception of the Barclay Member, which is a laterally extensive coal, other Middle Members appear to be more pod shaped. It is interesting to note that the marine incursion into coals is evident during the deposition of the Barclay Member. The lateral continuity of the Barclay Member is similar to Reading and Collinson's (1996) description of a humid lower delta plain blanket bog. Conditions necessary for a widespread bog are humid climates with a high water table. Such bogs are characteristically interrupted by clastic material (Reading and Collinson, 1996) which is only common in the Barclay seam to the north of the Kaitangata Sector. The depositional environment of the Middle Taratu Formation is hereby suggested to be a humid delta, similar to the modern Yallahs fan delta in Jamaica (Figure 3.12).

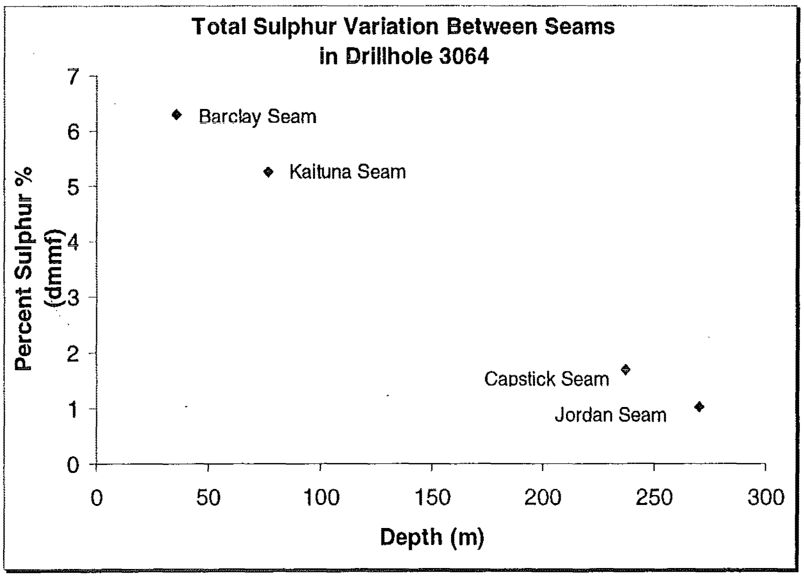


Figure 3.9: Sulphur variation between the Jordan and Capstick seams (Lower Members) and the Kaituna and Barclay seams (Middle Members).

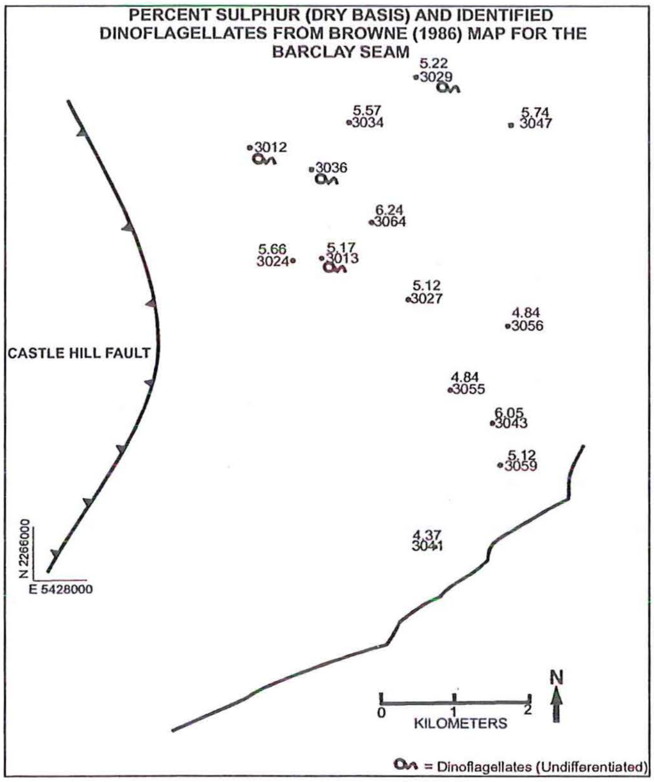


Figure 3.10: Coal sulphur percentage map with known dinoflagellate occurrences in the Barclay Member.

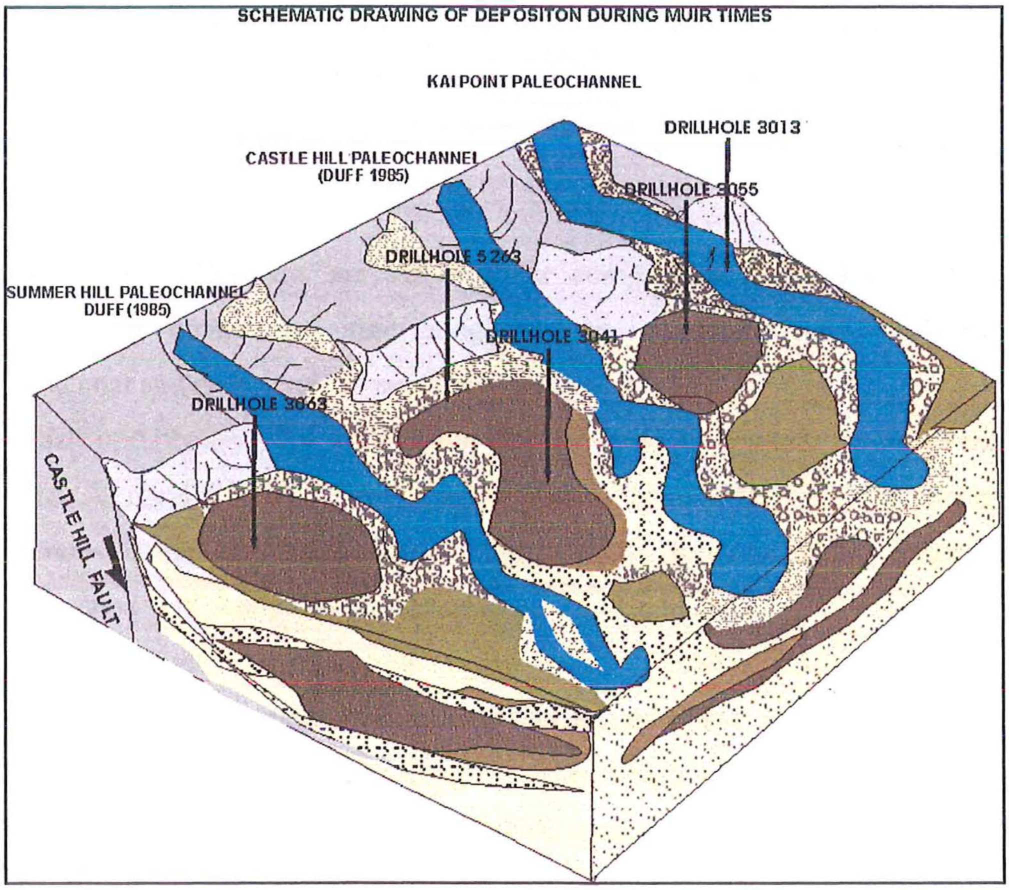


Figure 3.11: Schematic base diagram of the deposition during Muir deposition.

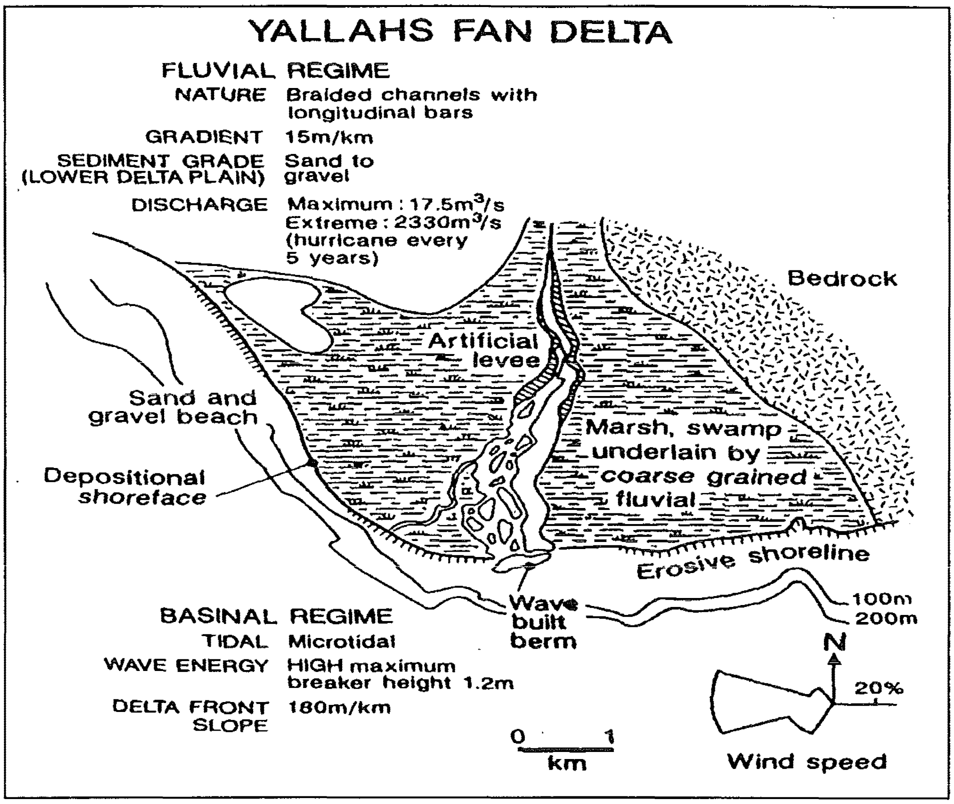


Figure 3.12: A modern humid climate alluvial delta, the Yallahs fan delta, Jamaica (Orton, 1988).

3.4.4 Upper Taratu Members

The Upper Taratu Members are very similar compositionally to the Middle Taratu Members, being quartz rich fine conglomerates, sandstones and mudstones with interbedded coal and carbonaceous mudstone horizons.

Coals initially are 1-2% sulphur, but increase up to 6% towards the top of the Taratu Formation. Vertically, coal development varies across the Benhar Sector with conglomerates prominently interbedded with coals in the Northern Benhar Sector and coals both interbedded with conglomerates, sandstones and mudstones in the southern Benhar Sector. Conglomerates are subangular to subrounded quartz mostly varying between granule to fine pebble conglomerates in size, McClelland (1984) notes that there are a high proportion of 'rod' shaped pebbles in conglomerates, which was also observed in this study at the outcrop of the Benhar seam at the Elliotvale opencast mine.

Cross-section F-F' (Appendix A) incorporates drillholes 3123 and 3007 in which basement was encountered. It appears that fine-grained facies and coals were deposited directly over basement on the western margin of Benhar Sector. However, across the Castle Hill Fault in the Kaitangata Sector in drillhole 3011, the Penman seam overlies and interfingers with conglomerates, suggesting that although Benhar Sector was low energy, the Kaitangata Sector was a moderate-high energy environment proximal to coal deposition. Evidently, during this time subsidence was still active on the Castle Hill Fault, this can be seen as the thickness of the Penman Member increases towards the Castle Hill Fault zone (Figure 3.15). The Penman Member is primarily composed of one and sometimes two thick low ash coal horizons, and although these increase in thickness towards the Castle Hill Fault, these members thin into carbonaceous mudstone (McClelland, 1984) and split when they encounter conglomerates (Figure 3.16).

The similarity of source between the Middle and Upper Taratu Members provides strength to the Duff's (1985) suggestion of a dominant northerly extrabasinal quartzose source. This is supported by the lack of coarse clastic material in the southern Benhar Sector around drillholes 3030 and 3021. Where coals progressively become more split to the north especially in the Benhar and Mount Wallace Members.

During Upper Taratu times sediment was primarily sourced from local basement and the borders of Benhar Sector, and also from paleochannels to the north. The depositional environment was a low-lying series of well-constrained channels to the north of the coalfield, which periodically overtopped their banks into the southern Benhar Sector. Cross-section E-E' shows the presence of conglomerates interrupting deposition. Drillhole 3114 shows a channel which pinches out laterally across the basin.

The depocenter of the Benhar Sector changed over the history of the Late Taratu members. Originally coals thickened towards the Castle Hill Fault during Penman deposition (Figure 3.15), but by Benhar Member the depocenter had moved into central Benhar Sector (Figure 3.14), becoming more proximal to the Castle Hill Fault again during the Mount Wallace deposition (Figure 3.13). It is speculative to describe the Upper Taratu Members distribution in the Kaitangata Sector as direct comparison with the Benhar Sector deposits cannot be achieved due to post depositional erosion. However, if paleochannels typically bypassed the Benhar Sector the Kaitangata Sector was probably a series of channels with interdistributary peats.

During Upper Taratu deposition there was still a marine influence on coals. The Benhar Sector was probably protected from the sea by a barrier bar (Raymond 1985), which was breached in Upper Benhar times, with the presence of dinoflagellates, noted by Browne (1986) in sandstone

The depositional environment for the Upper Taratu members, like the Middle Taratu Members, is compared to the Yallahs fan delta, Jamaica. In particular, the Benhar Sector is compared to the lake setting to the west on Figure 3.12.

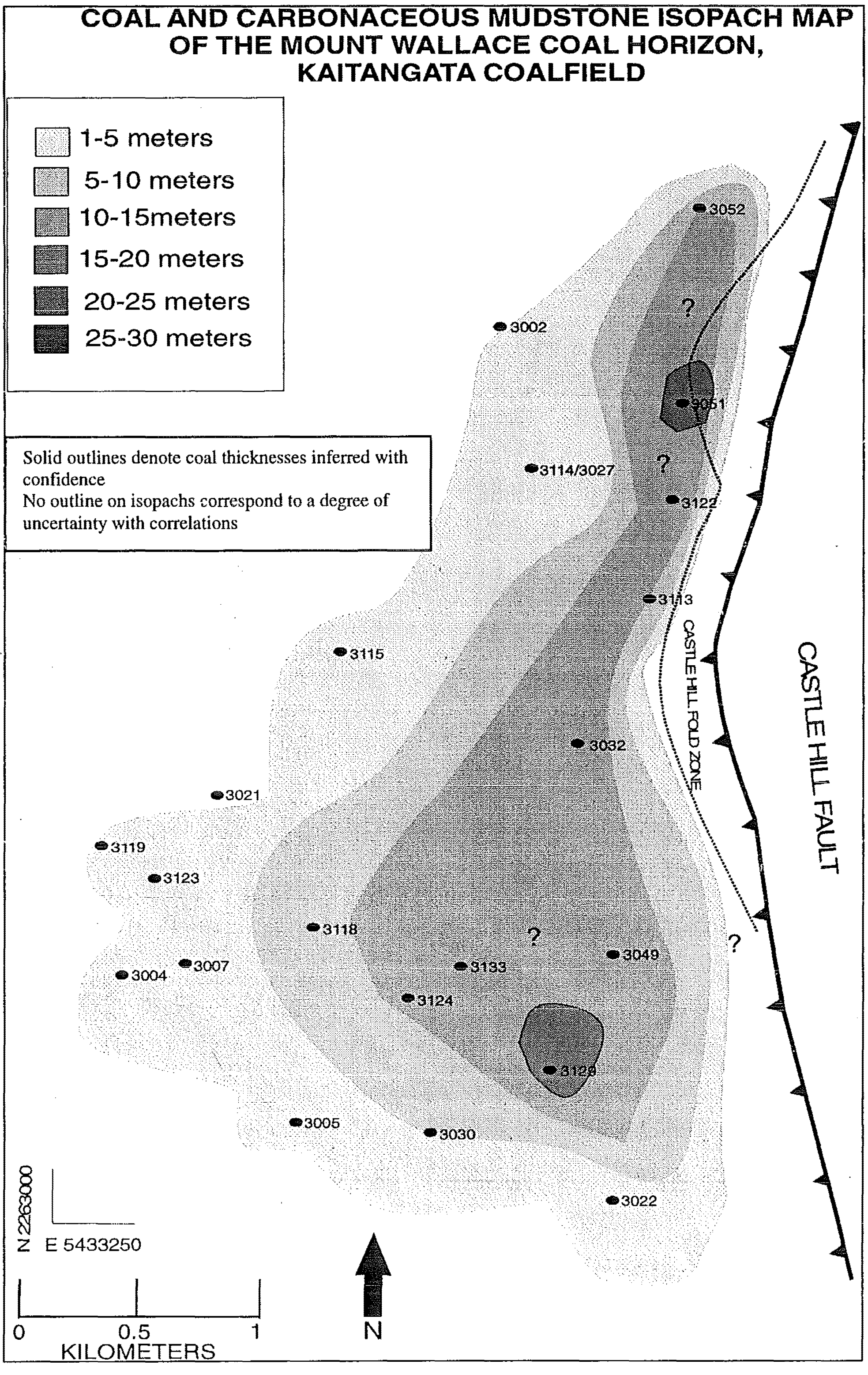


Figure 3.13: Coal and carbonaceous mudstone isopach distribution for the Mount Wallace coal horizon.

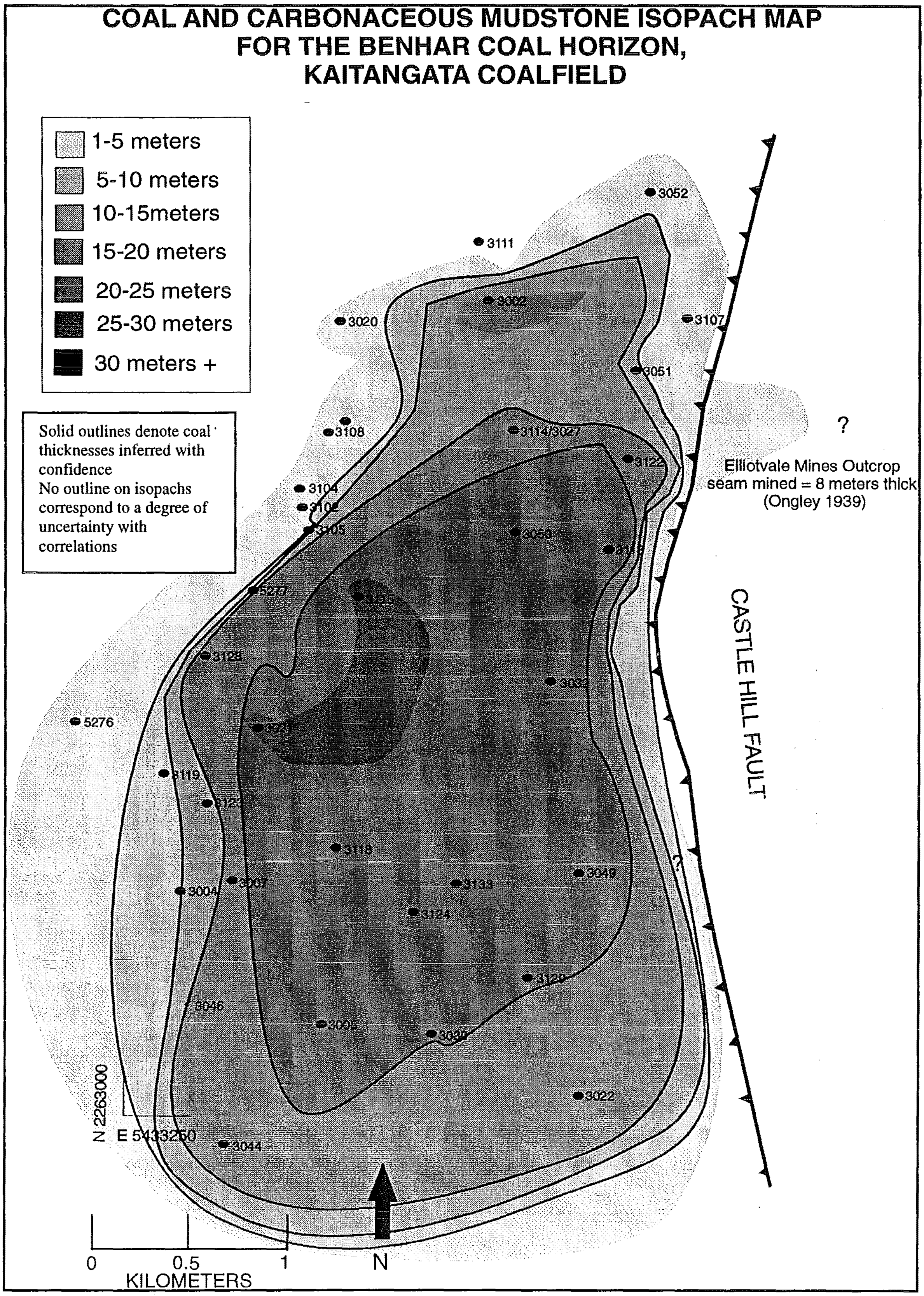


Figure 3.14: Coal and carbonaceous mudstone isopach distribution for the Benhar coal horizon.

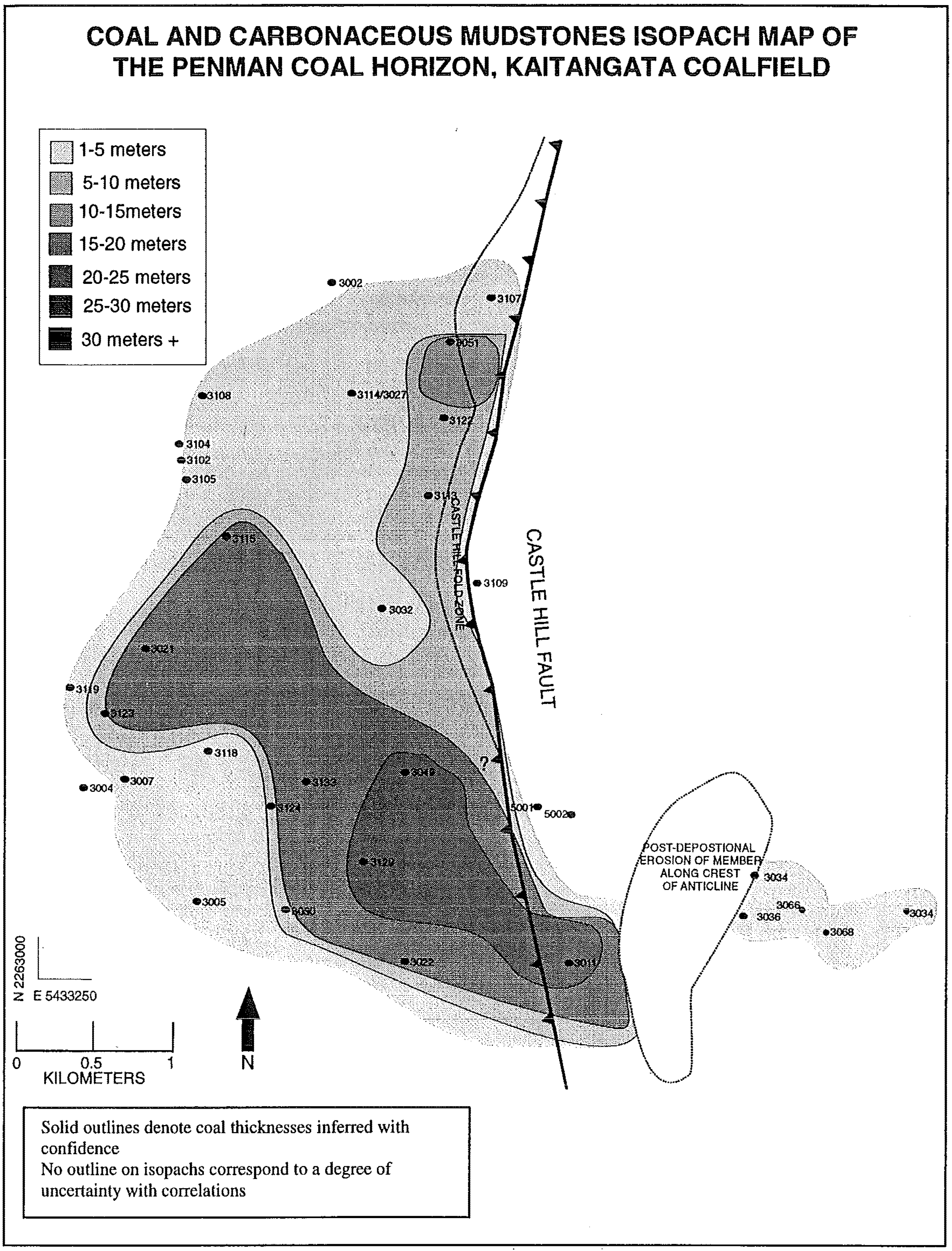


Figure 3.15: Coal and carbonaceous mudstone isopach distribution for the Penman coal horizon.

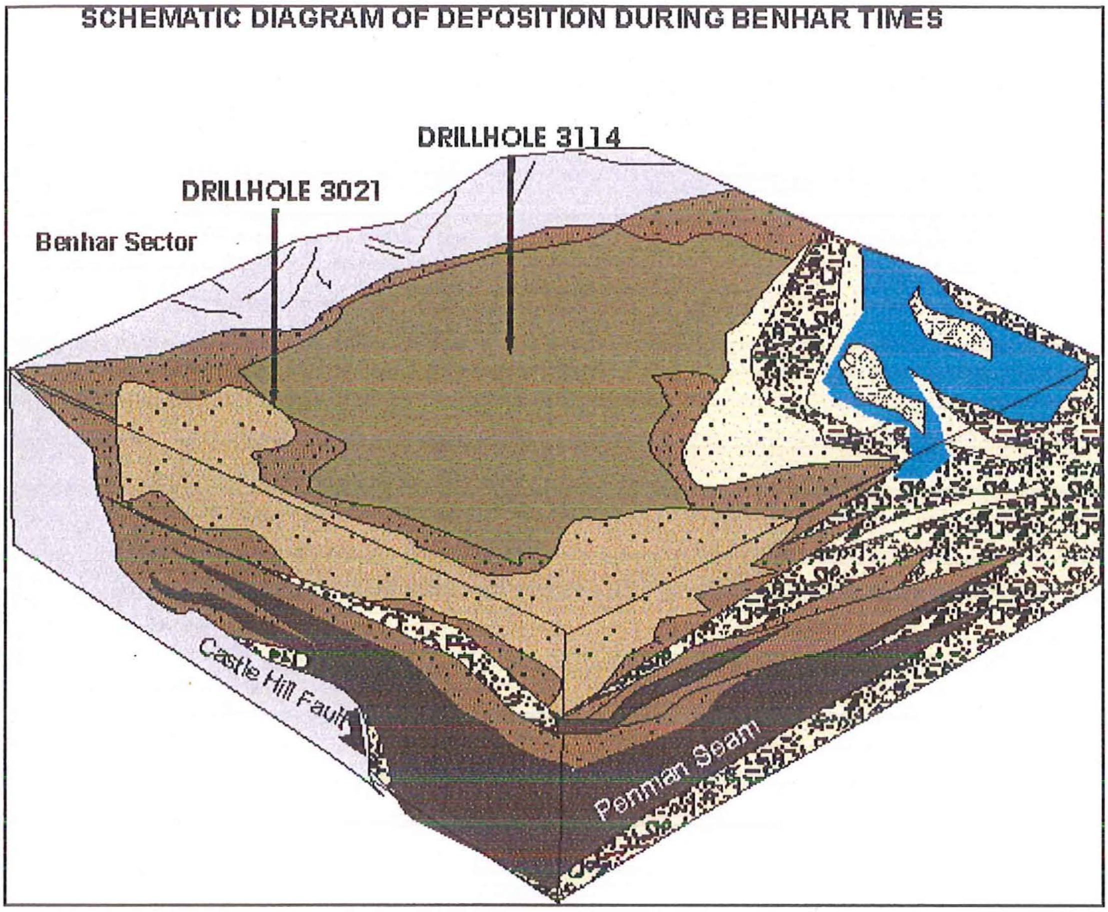


Figure 3.16: Base diagram of deposition during Benhar times. Note: the northerly influence of rivers causing seam splits and erosion of the Benhar and underlying Penman Member.

3.5 DEPOSITIONAL ENVIRONMENT OF THE TARATU FORMATION

In Summary, the depositional setting of the Taratu Formation changed over its history of the basin. During the deposition of the Lower Taratu Formation, the Kaitangata Coalfield was an alluvial fan in which basinal sediments were fed va paleochannels and directly off fault scarps. Peats were deposited in the proximal to the Castle Hill fault scarp and talus fan. Periodically during tectonic activity, peat swamps were intermittently interrupted by river channels, which both eroded peat and covered the swamp in thick conglomerates. As subsidence resumed, coals formed again on the periphery of the fault. During early Middle Taratu times the depositional setting of the basin changed altering in source of clastics, by the Middle to Upper Taratu times as influence of the Castle Hill Fault scarp reduced and was eventually buried during Penman times. At this stage extrabasinal sediments became dominant and a delta was built out from the north of Benhar Sector. As the delta retrograded seaward, probably concurrent with sealevel/climate fluctuations, a marine influence on peats occasionally occurred. This became more prominent until eventually after the Coombe Hay Member when marine conditions prevailed with the Wangaloa Formation transgressing over the basin.

CHAPTER FOUR

RANK TRENDS

4.1 INTRODUCTION

Various techniques are used in maturation studies to depict coal rank trends. The most common tool is the use of vitrinite reflectance (VR), which measures the reflective properties of the coal maceral vitrinite. However, coal chemical information attained from moisture, calorific value (CV) and volatile matter (VM), can also give important rank information relating to a basin's thermal history.

The Kaitangata Coalfield has extensive coal deposits, which vary in rank from ASTM classification lignite B to sub-bituminous B. Coal maturation studies previously completed in the Kaitangata Coalfield have included chemical assessment of coal quality using Calorific Value (CV), bed moisture and sulphur (Suggate, 1959; McClelland, 1984). However, these have not been previously placed within a stratigraphic framework and compared to other analyses, such as VR. Moreover, these have not been interpreted for basinal trends using Suggate Rank (SR).

4.1.1 Coal Rank: Background

Rank refers to the degree of metamorphism as coals are chemically and physically altered through various grades of coalification. This follows the peatification process and begins with lignites, progressing through sub-bituminous, bituminous, semi-anthracite and anthracite coals and then a final and maximum alteration to graphite (Suggate, 1959). The degree of coalification experienced is regarded as the coals' rank and can be attributed to many parameters, such as burial metamorphism, contact metamorphism, faulting and tectonic stresses (Suggate, 1959; Stach, *et al.*; ,1982; Ward, 1984; Taylor, *et al.*, 1998).

Depth of burial is recognised as the most important factor influencing coal rank. This is primarily the result of an increase of temperature that the coal experiences with depth, known as Hilt's Law (e.g., Ward, 1984; Teichmüller *et al.*, 1998). Temperature increases with depth following the geothermal gradient and this is intimately related to the basins history, and thus, can vary over space and time. Therefore, a coal buried in a basin with a high geothermal gradient does not require as much burial to achieve the same rank as a coal buried in a basin with a lower geothermal gradient (Suggate, 1959; Stach, *et al.* 1982; Suggate, 1998; Taylor *et al.*, 1998).

Contact metamorphisms from igneous intrusives have been known to affect coals on dramatically different scales. An igneous intrusion may have a very localised affect; for example, Suggate (1959) noted that in old mines in Canterbury, New Zealand, that lignite passes laterally into anthracite within several meters of a dyke, which intruded the coal seam. Alternatively, an area may be regionally affected, for example; the Miocene Pannonian Basin, Austria, where coal seams near Miocene volcanoes have experienced extremely high geothermal gradients of 300 mega watts per square meter, corresponding to burial depths of less than 2 km. This has resulted in vitrinite reflectance values of 4% (anthracites). These random reflectance values decrease to 1% (high volatile A bituminous rank) several kilometres from the volcanic centre (Sachenhofer and Littke, 1993).

Faulting may also be a factor influencing coal rank. During active faulting, especially in strike-slip basins, localised increases in rank have been observed from frictional stresses with localised geothermal gradient increases (Taylor, *et al.* 1998). Faulting due to extensional tectonics in the Rhine graben, have resulted in high heat flow along faults influencing coal rank near faults (Teichmüller and Teichmüller, 1979).

4.1.1.1 Vitrinite Reflectance

Vitrinite reflectance is a commonly used diagnostic tool in assessing maturation levels of strata by the petroleum industry. Suggate (1998) describes vitrinite reflectance as a thermometer measuring the maximum temperature experienced by organic particles. The rank reached by the coal is then 'fossilised' unless the thermal regime of the basin is altered by reburial, contact metamorphism, or by an increased heat flow (Suggate, 1998).

The vitrinite maceral group is intermediate in reflectance between inertinite and liptinite (Stach, *et al.* 1982; Taylor, *et al.* 1998). Vitrinite originates from the preservation of stems, roots, leaves and wood of plants. This includes the periderm and mesophyll tissues. Vitrinite is also formed by gellification of humic material (Stach, *et al.* 1982). Essentially, vitrinite is composed of different humins made of an aromatic nucleus surrounded by alphatic groups (Stach, *et al.* 1982). As the reflectance of vitrinite increases, these humins condense, resulting in an increased reflectance (Sykes, *et al.* 1991).

Vitrinite reflectance is preferred to the reflectance of other coal macerals, not only because vitrinite is the predominant maceral component in coals, but also because it shows a steady increase in reflectance with rank. This does not occur with the same reliability in other coal maceral groups (Figure 4.1) (Stach, *et al.* 1982; Teichmüller, 1998).

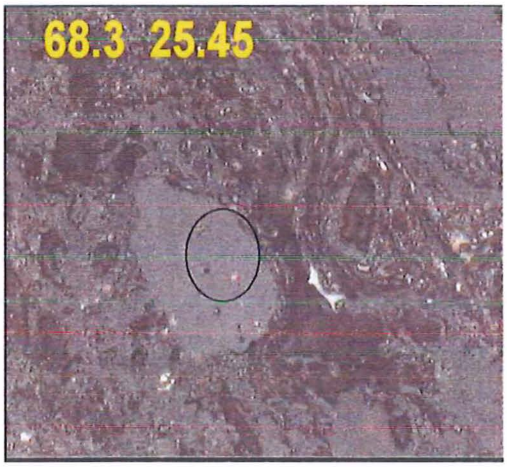


Figure 4.1: Example of telovitrinite (the vitrinite submaceral used for measurement in this study) from the Jordan coal horizon, drillhole 3064, Kaitangata Coalfield. The area circled indicates the area of measurement for vitrinite reflectance (photo taken by Jane Newman, 2003).

Vitrinite reflectance accurately reflects rank in high rank coals (<0.5 % R_o), but is much less accurate in lower rank coals, (Sykes, *et al.* 1991). This is due to variables related to inherent properties of the coal (e.g. coal type), or diagenetic changes during peatification and early burial (e.g. humification). At low ranks, many chemical, physical and petrological changes occur in coals, especially between the lignite sub-bituminous C rank stages (Teichmüller *et al.*, 1998). During this transition, coal constituents are not well defined. As the coal increases in rank, the ratios of oxygen and hydrogen reduce relative to an increase in carbon (Stach, *et al.* 1982). Such changes in the coals composition can also be seen in the coals physical structure, with low rank coals characteristically more porous and with variable reflectances (Taylor *et al.*, 1998). Therefore, care must be taken when applying VR to low rank coals.

4.1.1.2 Calorific Value and Volatile Matter

The constituents which make up a coal's composition can vary to some degree. This is dependant on the coal's derivation from the initial depositional environment (organic and inorganic component), which is further modified by diagenesis and metamorphism (Ward, 1984). Coal is typically composed of a mixture of organic compounds with an inorganic component (mineral matter) (Ward, 1984). The components that make up coal, can be measured using laboratory techniques to establish the degree of coalification experienced (see section 2.4.2 for description of coal chemistry analysis).

The energy released from a coal when combusted is primarily the result of the interaction of hydrocarbon compounds with oxygen (Ward, 1984). The measurement of the energy released from coal is known as its calorific value or specific energy. As a general rule, as the rank of a coal increases so does the calorific value, and thus it is used as a good indicator of the coal rank.

Volatile matter refers to the constituents of coal that are liberated at high temperatures, excluding the moisture content. This can include mineral moisture from clays and organic compounds from the coal itself. Typically, as a coal increases in rank the volatile matter component decreases due to a loss in porosity (Ward, 1984).

4.2 RANK TRENDS IN THE KAITANGATA COALFIELD

Vitrinite Reflectance (VR), Calorific Value (CV) and Suggate Rank (S_r) plots using CV and volatile matter (VM), were used to assess rank trends vertically and laterally across the Kaitangata Coalfield. Coal rank using VR varied from 0.28 R_o Random to 0.41 R_o Random, CV ranged from 10743 to 13646 Btu/lb and Suggate Rank varied from 0.8 to 7.8 S_r units, covering the ASTM rank range of Lignite B to Sub-Bituminous B.

Downhole trends were measured using VR, which were then compared with CV (Btu/lb) that had been corrected to a dry mineral matter sulphur free basis (dmmsf). VR data showed generally that coal rank did increase with depth, with the most notable rank difference occurring between the Middle and Lower Taratu Members. The Middle-Upper Taratu Members showed downhole increases in rank, but these trends were often within the accepted limit for lateral seam variation. Lateral variations in coal rank were hard to depict using VR. However, CV values showed lateral trends in the Benhar Sector with the Mt. Wallace, Benhar and Penman coal horizons all increasing in rank towards the Castle Hill Fault. Lateral trends in the Kaitangata Sector were hard to depict because of poor data coverage, although a possible trend between the Barclay Member may be depicted. Suggate Plots supported rank variability laterally within Taratu Members, although lateral trends were not as obvious as in the CV isopach maps.

A complete collection of VR data can be found in Appendix C. Suggate Rank figures can be found in Appendix G. A data C.D., which includes all raw data used to create all coal chemistry analyses, can be found in Appendix E.

4.2.1 Kaitangata Sector Downhole Rank Trends

The number of VR analyses made were limited in the Kaitangata Sector because of a lack of available drillcore material for vitrinite reflectance sampling. However, drillholes 3055, 3057 and most importantly 3064, provided good depth parameters.

4.2.1.1 Drillhole 3064

The most complete data set was obtained from drillhole 3064 (Figure 4.2). VR measurements showed a distinct downhole increase from 0.36-0.34 R_o in the Barclay and Kaituna seams, to 0.39-0.41 R_o in the Capstick and Jordan seams. A downhole rank gradient can therefore be estimated at 0.07% R_o over 185.2m between the Kaituna and Jordan seams, which equates to a rank change of 0.038 R_o/100m. However, rank variation between the Barclay, Kaituna and Capstick seams cannot be compared with confidence as they fall at the limits of VR error of $\pm$ 0.05 R_o.

Calorific Values showed a general increase with depth, but like the VR data showed some fluctuation. The CV values between the Barclay and Kaituna seams were within the error limits of $\pm$ 164 Btu/lb, disregarding any rank variation between the two members. However, a rank increase from 12648 to 13039 Btu/lb occurs over 159 m between the Kaituna and Capstick seams, equating to a rank increase of 505 Btu/lb/100m. Rank variation using CV was not obvious between the Capstick and Jordan Member. The Capstick seam shows a slightly higher CV of 13039 Btu/lb compared with the Jordan seam value of 13001 Btu/lb. This is well within the error limits accepted for Btu/lb, making a judgement on rank between these two seams negligible.

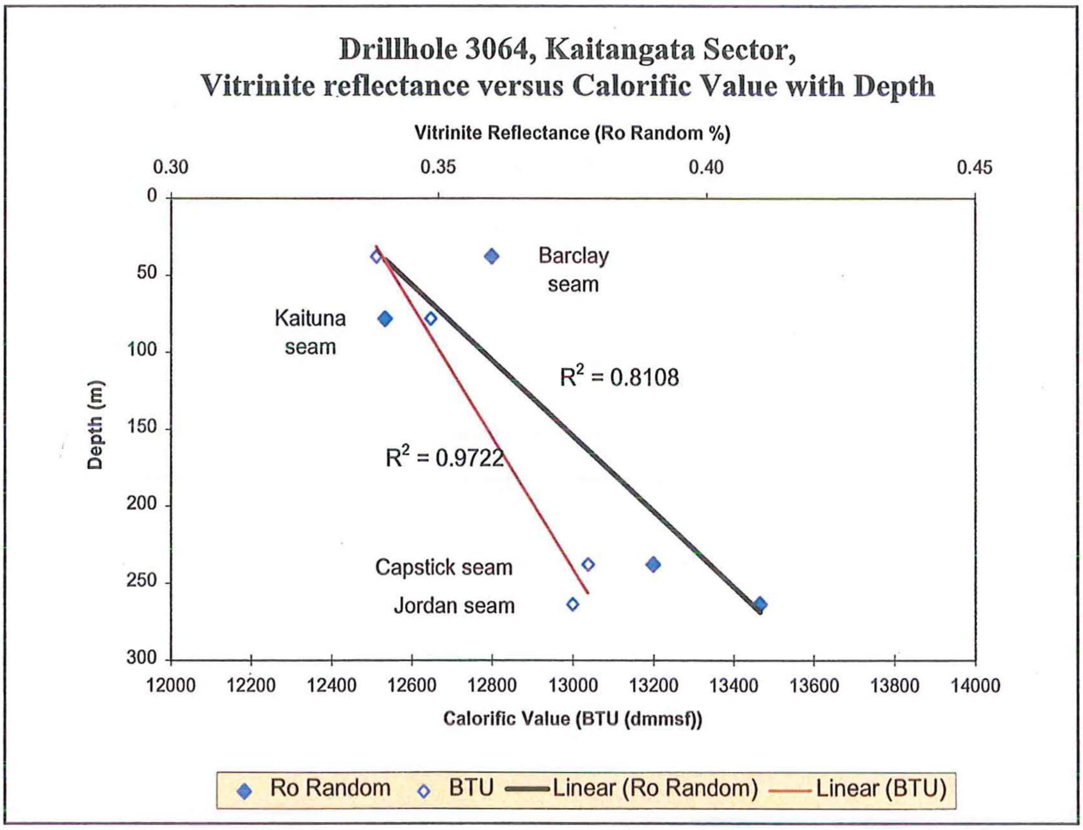


Figure 4.2: Relationship between depth, vitrinite reflectance and calorific value in Drillhole 3064.

A Suggate Rank plot using CV versus VM were used to illustrate an overall increase in rank downhole (Figure 4.3). In Suggate Rank plots, an increase in rank is plotted laterally, with rank increasing to the left, whereas variation in coal type are plotted along the more vertical isorank lines (see Chapter 2, Figure 2.7 for explanation). The four seams plotted show an increase in rank according to the stratigraphic position of the member. The Barclay and Kaituna seams occur at depths of 37.86 and 78.35 meters and show similar Suggate Ranks of 4.8 and 4.9 (with some small type variation). This can also be seen in the Capstick and Jordan seams at depths of 237.7 and 263.56 meters, which plot values of 6.8 and 6.9 S_r respectively. Suggate plots show rank increases that were not so obvious using VR and CV as single parameters, although general trends are supported by all forms of analysis. An overall rank increase is shown between the Middle (Barclay and Kaituna seams) and Lower Taratu Members (Capstick and Jordan seams).

Although there was fluctuation in rank between different coal members, the overall trend of drillhole 3064 showed a downhole increase in rank.

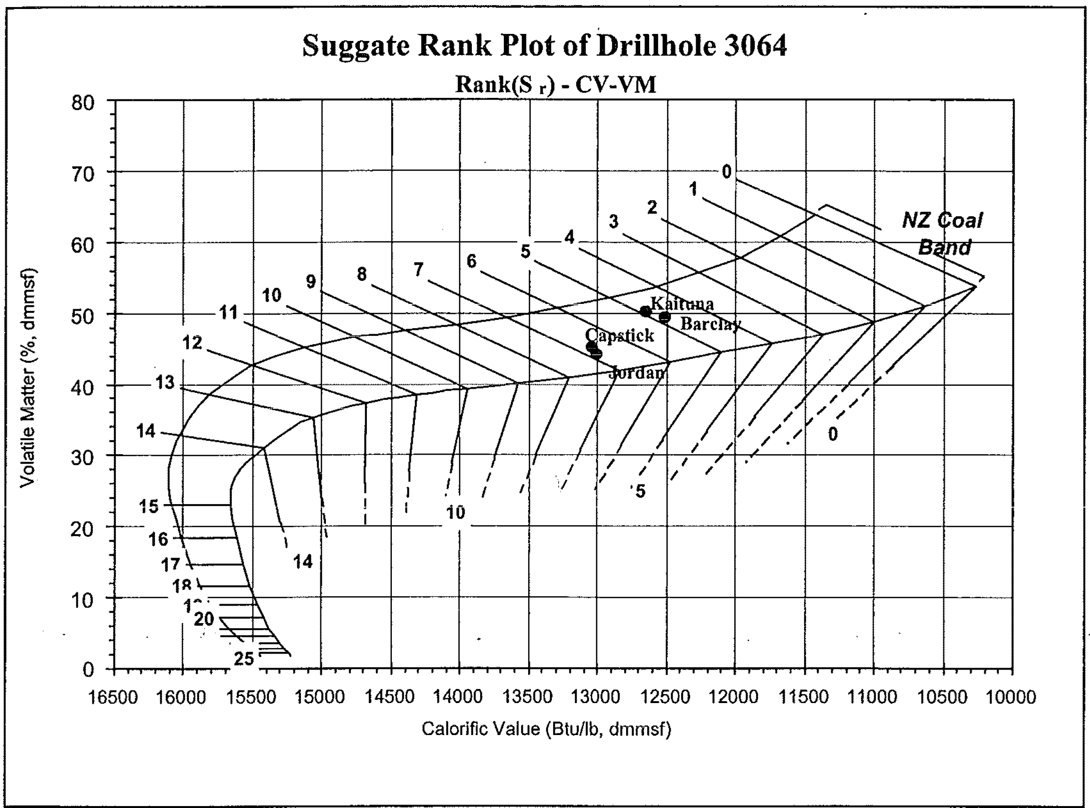


Figure 4.3: Suggate Rank plot showing a progressive increase of rank with depth in the Taratu Formation Members of Drillhole 3064.

4.2.1.2 Drillhole 3055

Two samples were analysed for VR from drillhole 3055 (Figure 4.4). The upper sample from the Barclay seam gave a VR of 0.33 R_o and a CV of 12672 Btu/lb. The lower sample from the Jordan seam measured 0.41 R_o, showing a rank increase of 0.08 R_o between the two seams over 220.26m. This equates to a rank increase of 0.036 R_o /100m. As only one CV data point exists there can be no comparison between Btu/lb and VR values.

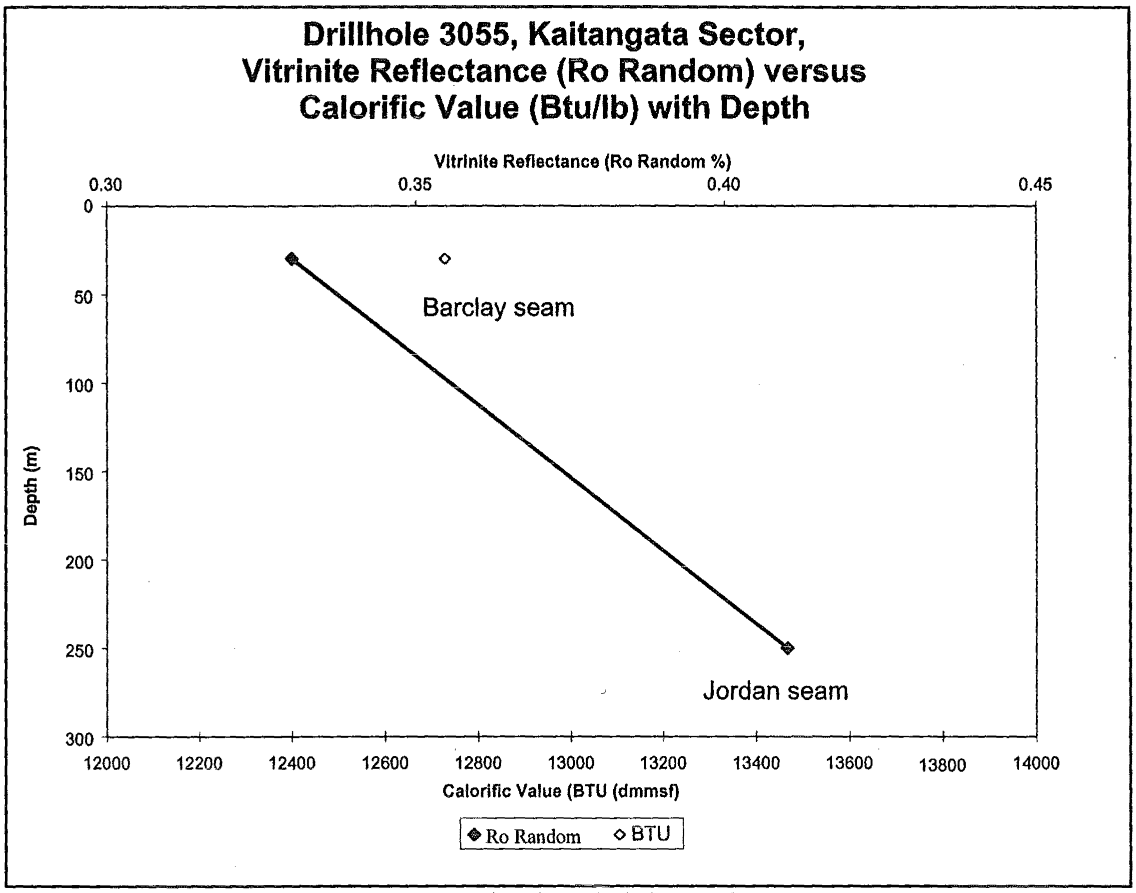


Figure 4.4: Relationship between depth, vitrinite reflectance and calorific value in Drillhole 3055.

4.2.1.3 Drillhole 3057

Similar to drillhole 3055, drillhole 3057 presents only one data point for CV, so that a comparison with VR could not be achieved. Drillhole 3057 provided data on the Capstick and Jordan seams, both of which belonging to the Lower Taratu Members (Figure 4.5). Although the Capstick coal horizon is stratigraphically higher than the Jordan seam by 48 meters, the Capstick coal horizon showed a higher reflectance of 0.37 R_o, whereas the Jordan coal horizon is 0.36 R_o, resulting in a negligible rank difference within the error limits of ±0.05 R_o for the VR technique.

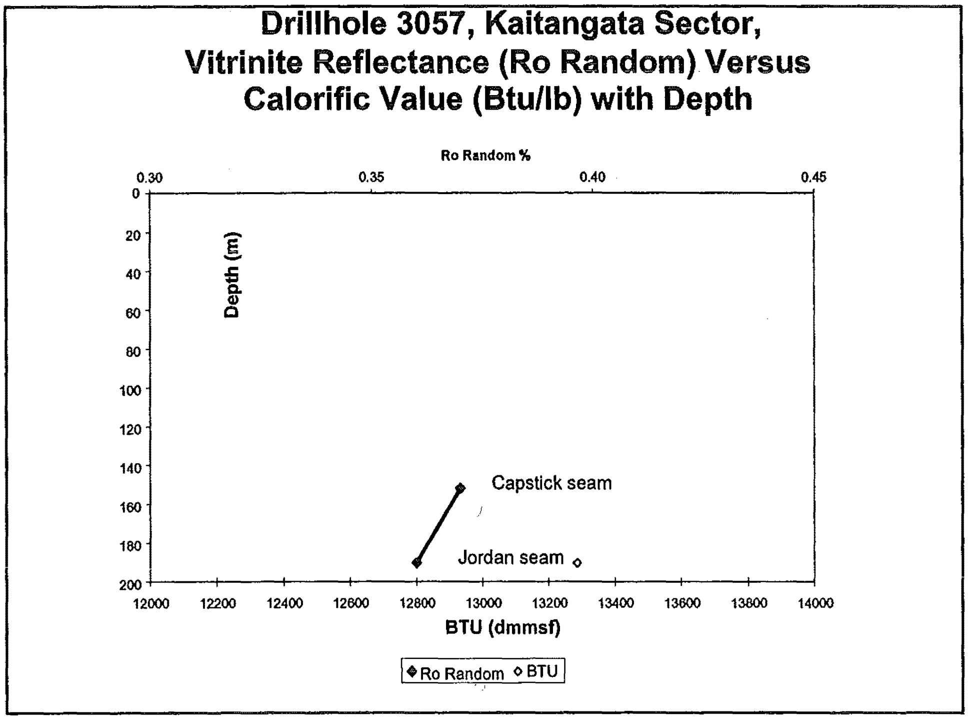


Figure 4.5: Relationship between burial depth, vitrinite reflectance and calorific value in drillhole 3057.

4.2.2 Lateral Rank Trends, Kaitangata Sector

Lateral rank variation within the Kaitangata Sector has been compiled for the Washpool, Barclay, Kaituna, Capstick, Jordan and Kai Main seam horizons. VR data was not extensive enough to interpret lateral rank variation. However, CV and VM data from various drilling reports (Barry, 1982. McClelland, 1984, Duff and Barry, 1985) were collated and used to create CV rank isopach maps and Suggate Rank plots (see Appendix G).

4.2.2.1 Kai Main Coal Horizon

Lateral CV data for the Kai Main coal horizon suggested no obvious lateral rank trends (Figure 4.6). The data set is restricted and this may explain a lack of variability. Suggate Rank plots show some variability with rank, from 4.5 Sr to 7.1 Sr units, although this is predominantly the result of two outliers, drillholes 5217 and 5248 and apart from these drillholes the Kai Main coal horizon has a tight distribution between 6.5 and 7.1 Sr units (Figure 4.7).

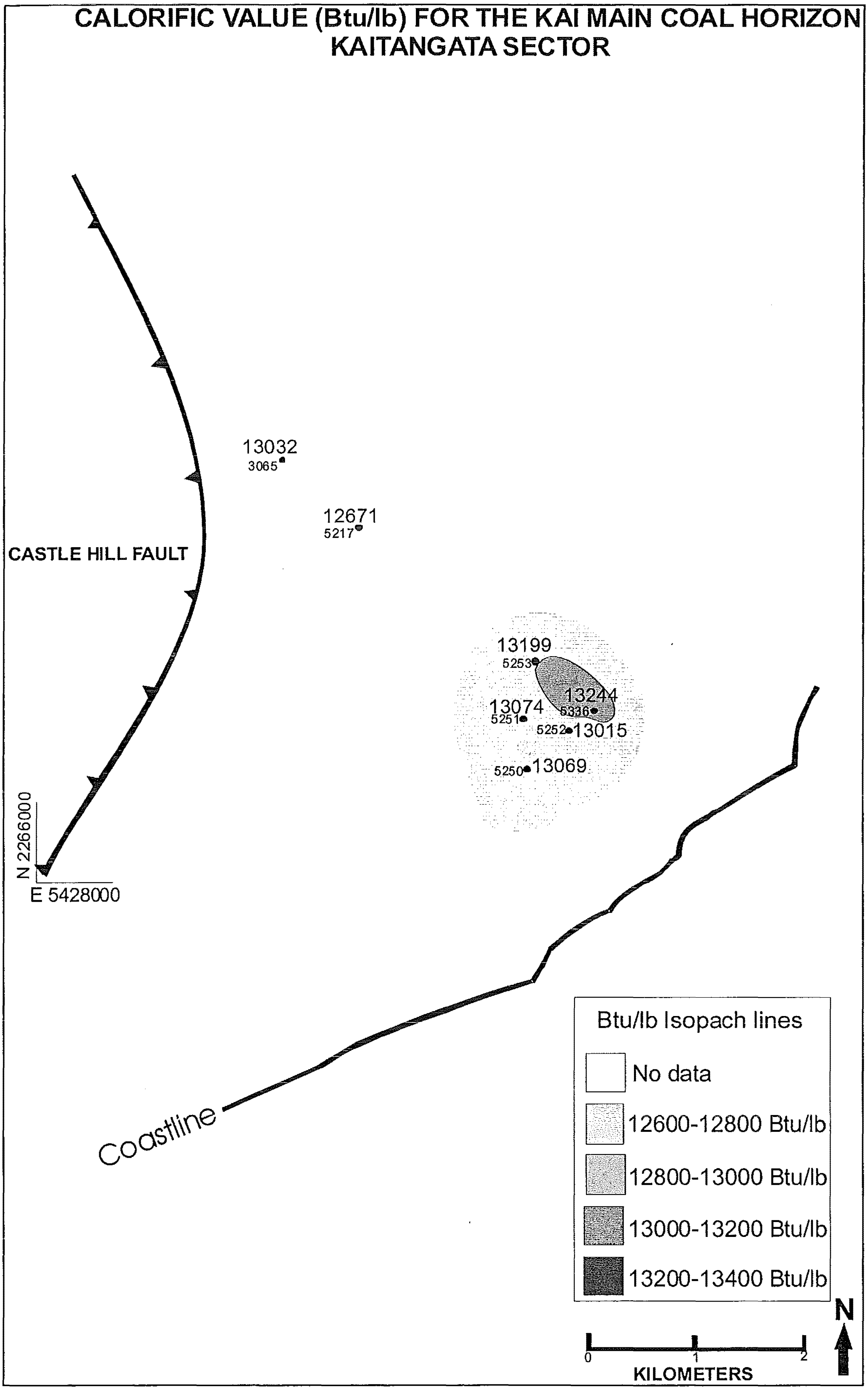


Figure 4.6: Calorific Value (CV) isopach map for the Kai Main coal horizon.

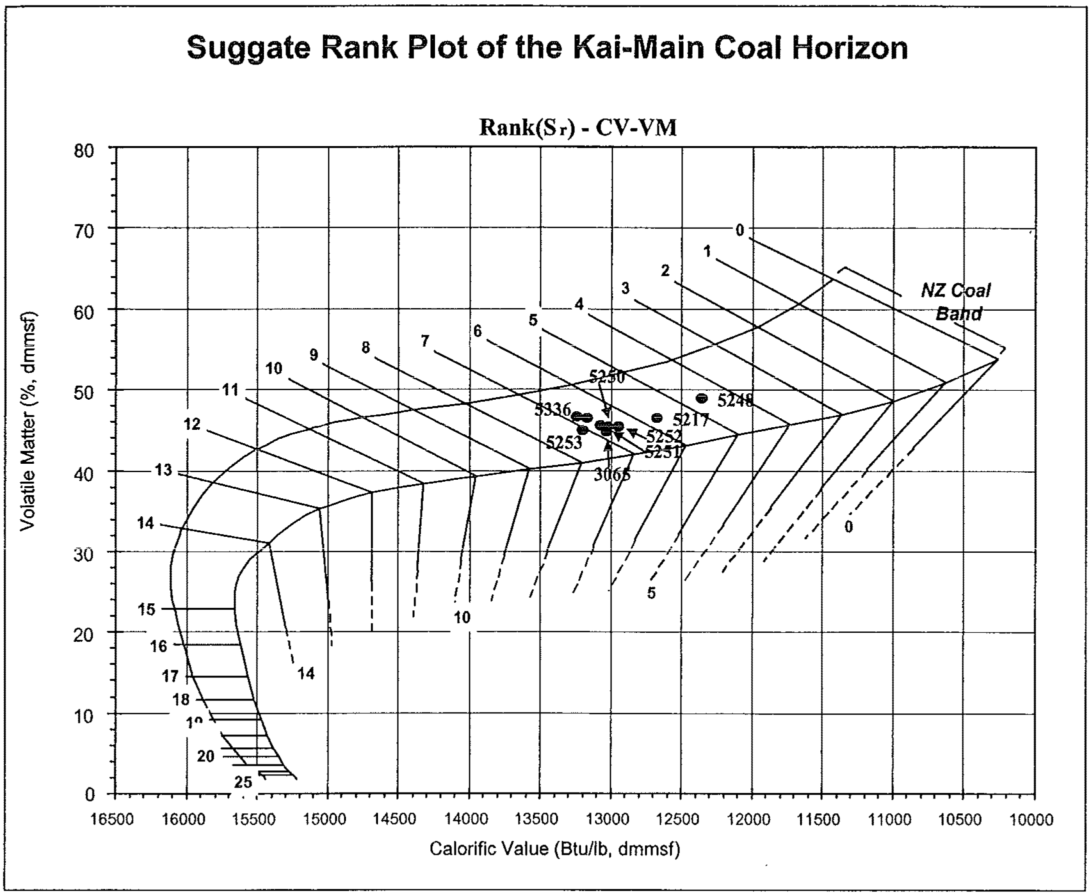


Figure 4.7: Suggate Rank plot (CV-VM) showing lateral rank variation of the Kai Main Member in various drillholes.

4.2.2.2 Jordan Coal Horizon

CV data is also limited in the Jordan coal horizon. However, a rank increase can be noted around drillholes 5255, and 3057 (Figure 4.8). A Suggate Rank plot supports this CV rank trend and shows almost all Jordan drillholes are plotting between 6.2-7 S_r units, apart from drillhole 5249, which has a value of 5 S_r units (Figure 4.9).

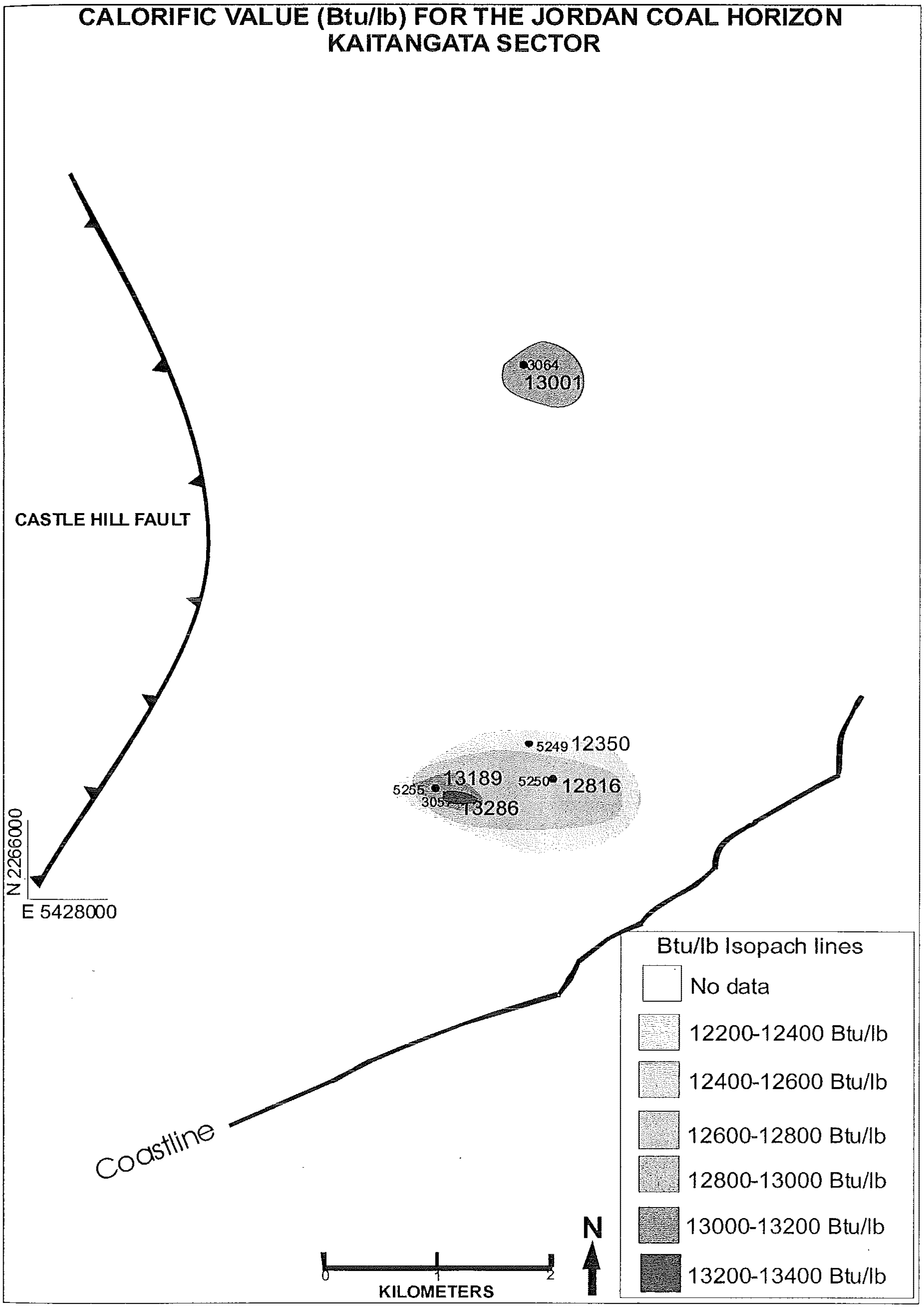


Figure 4.8: Calorific Value (CV) isopach map for the Jordan coal horizon.

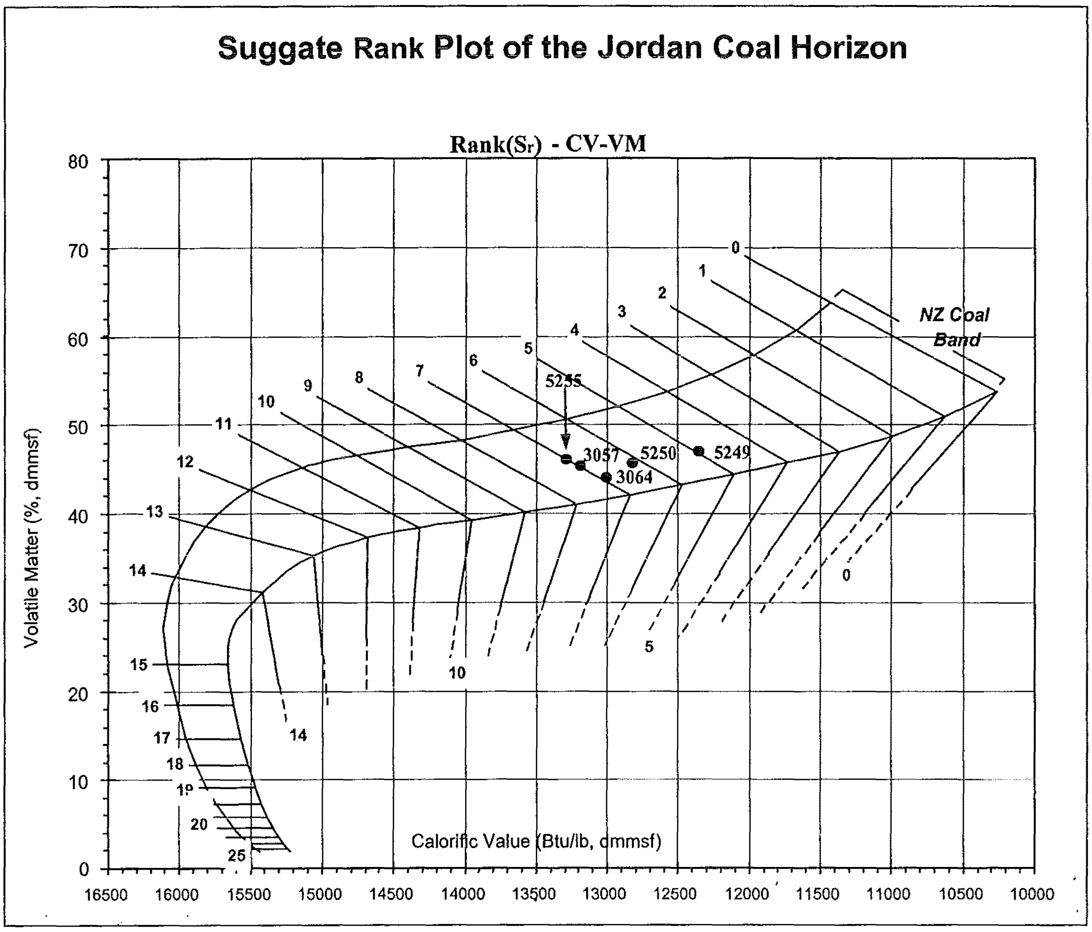


Figure 4.9: Suggate Rank plot of lateral rank variation in the Jordan coal horizon.

4.2.2.3 Capstick Coal Horizon

There was insufficient data within the Capstick coal horizon to compare VR for lateral trends. Similar to the Jordan coal horizon, the Capstick seam shows an increase in CV in the same areas (Figure 4.10). Suggate Rank plots of the Capstick coal horizon shows significant lateral rank variation within the horizon with rank varying from 5.5 to 7 S_r units (Figure 4.11). This is unexpected as most of these drillholes are densely spaced over a laterally restricted area. This indicates that there are either dramatic rank changes over a small area, or that this data may be subject to error from the corrections that were used. This will be discussed in detail in section 4.2.7.

4.2.2.4 Broome Coal Horizon

Only one sample was available for VR on the Broome Member. This was collected from drillhole 3013 of the Broome coal horizon. The Broome seam sample showed a vitrinite reflectance reading of 0.36 R_o. Only one CV data point exists. And has been included in a combined plot of all coals with limited data (Figure 4.21). As this section discusses lateral variation, these samples could not be used.

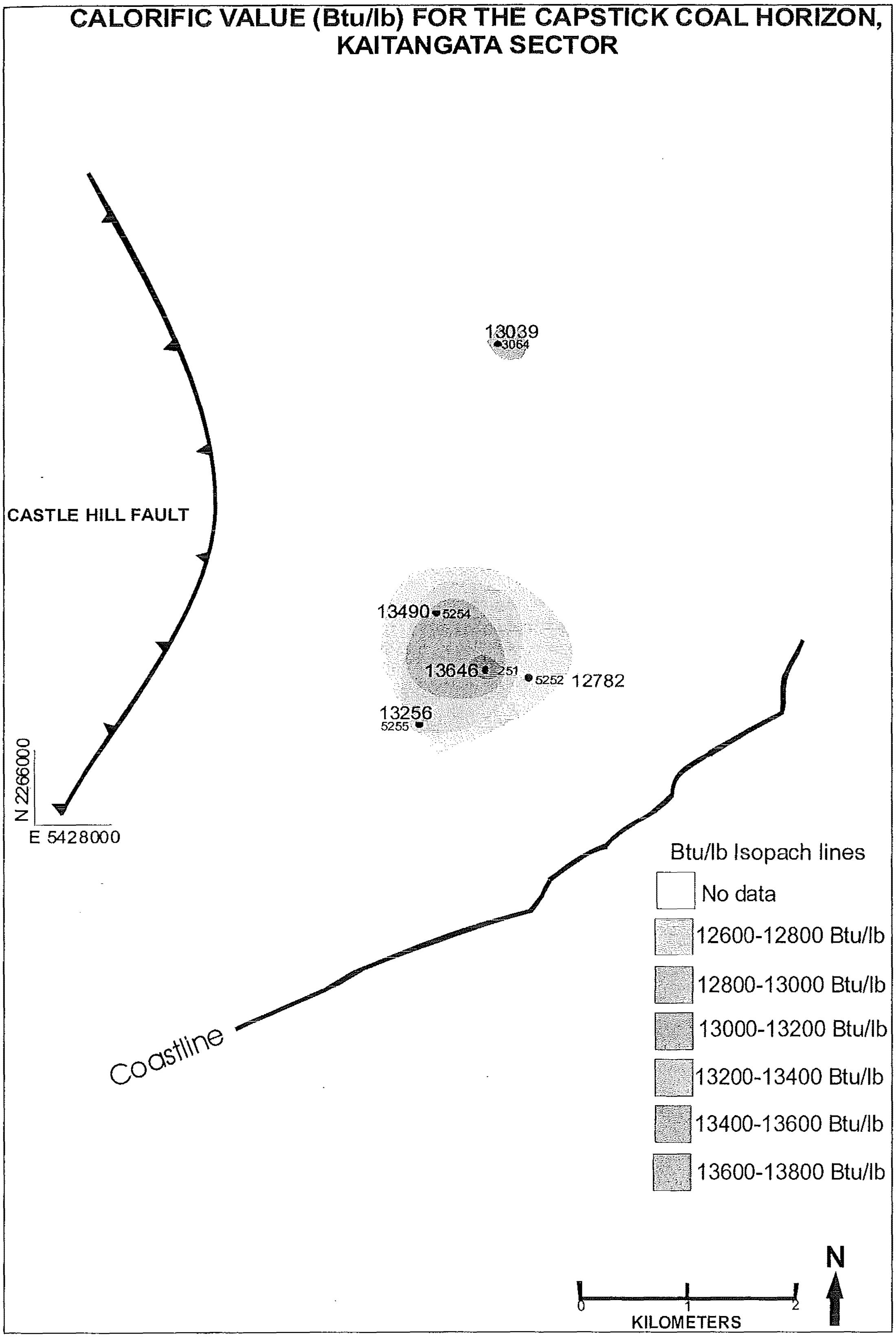


Figure 4.10: Calorific Value (CV) isopach map for the Capstick coal horizon.

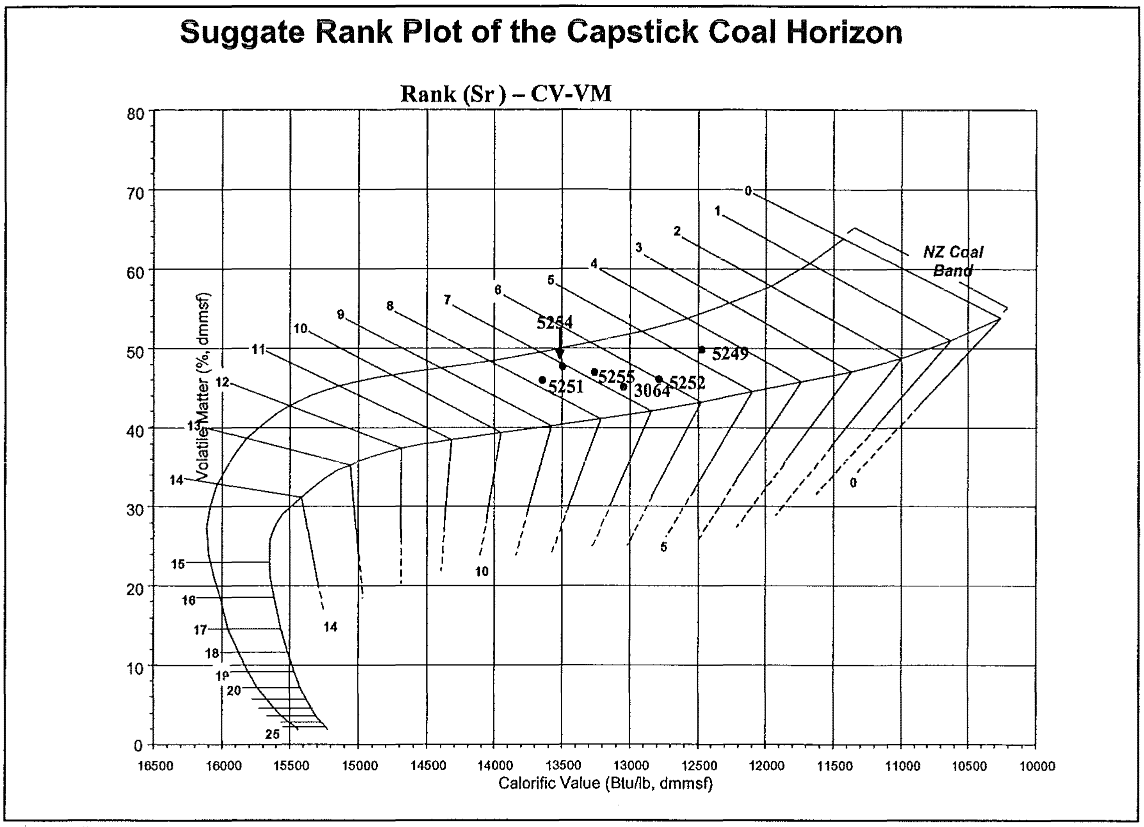


Figure 4.11: Suggate Rank plot showing lateral variation in the rank of the Capstick coal horizon.

4.2.2.5 Kaituna Coal Horizon

Two samples were collected for vitrinite reflectance on the Kaituna coal horizon. These were taken from drillholes 3012 and 3064. Both these samples had a reflectance reading of 0.34 R_o. Figure 4.12 shows the lateral variation of CV data for the Kaituna coal horizon. Lateral rank varies from 12648 Btu/lb in drillhole 3064 to a maximum of 13148 in drillhole 3028, located immediately 650m to the north-east of drillhole 3064. Conversely, the Suggate Rank plot showed very little rank variation in the Kaituna coal horizon, with most samples plotting values between 5-6 S_r units (Figure 4.13). The Suggate rank plot also showed evidence of strong type variation within the Kaituna coal horizon. This is depicted by coals plotting across the entire New Zealand coal band, and in the case of drillhole 3012, above the New Zealand coal band. A discussion on type variation and coal rank is given in section 4.2.7.1.

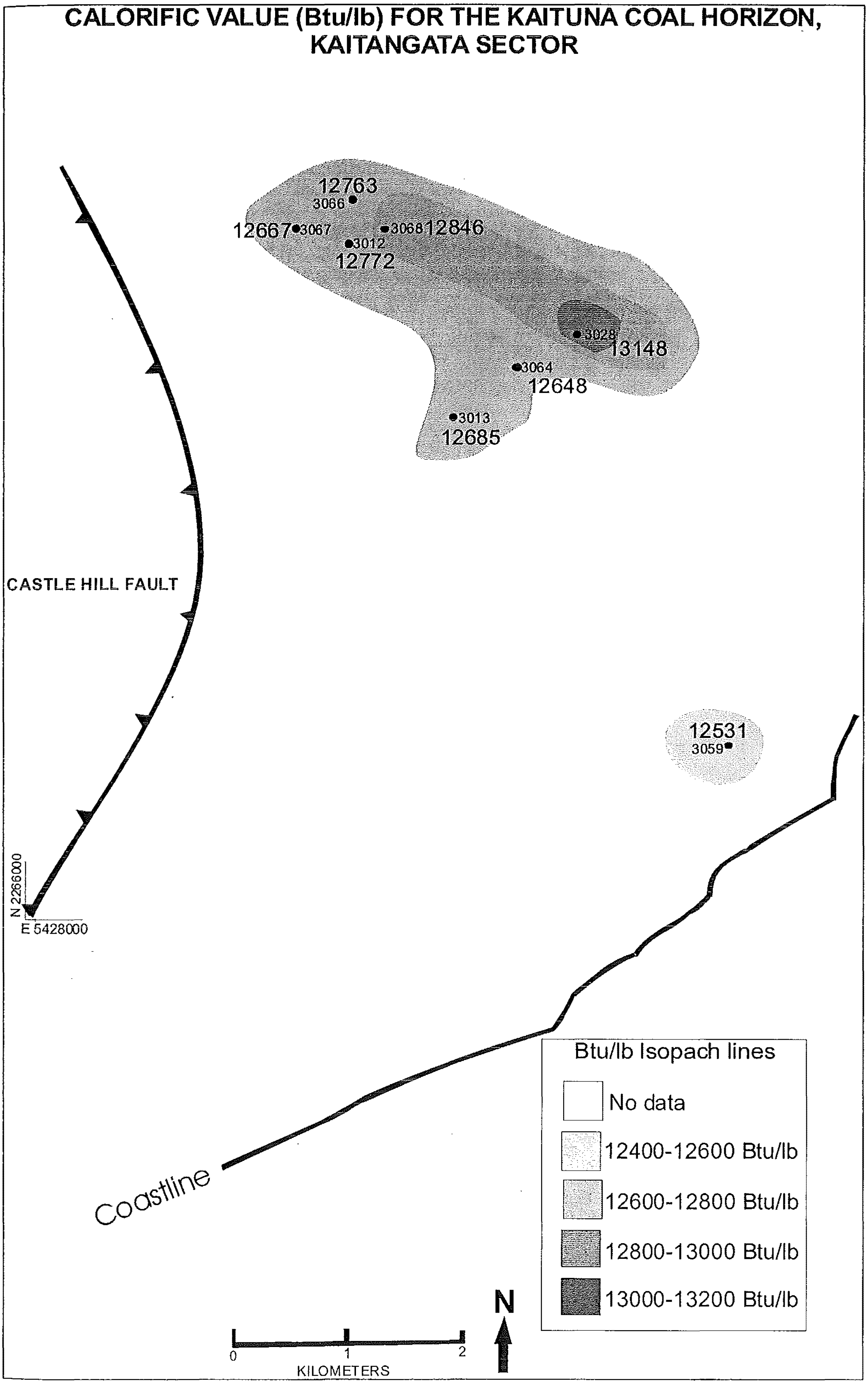


Figure 4.12: Calorific Value (CV) isopach map for the Kaituna coal horizon.

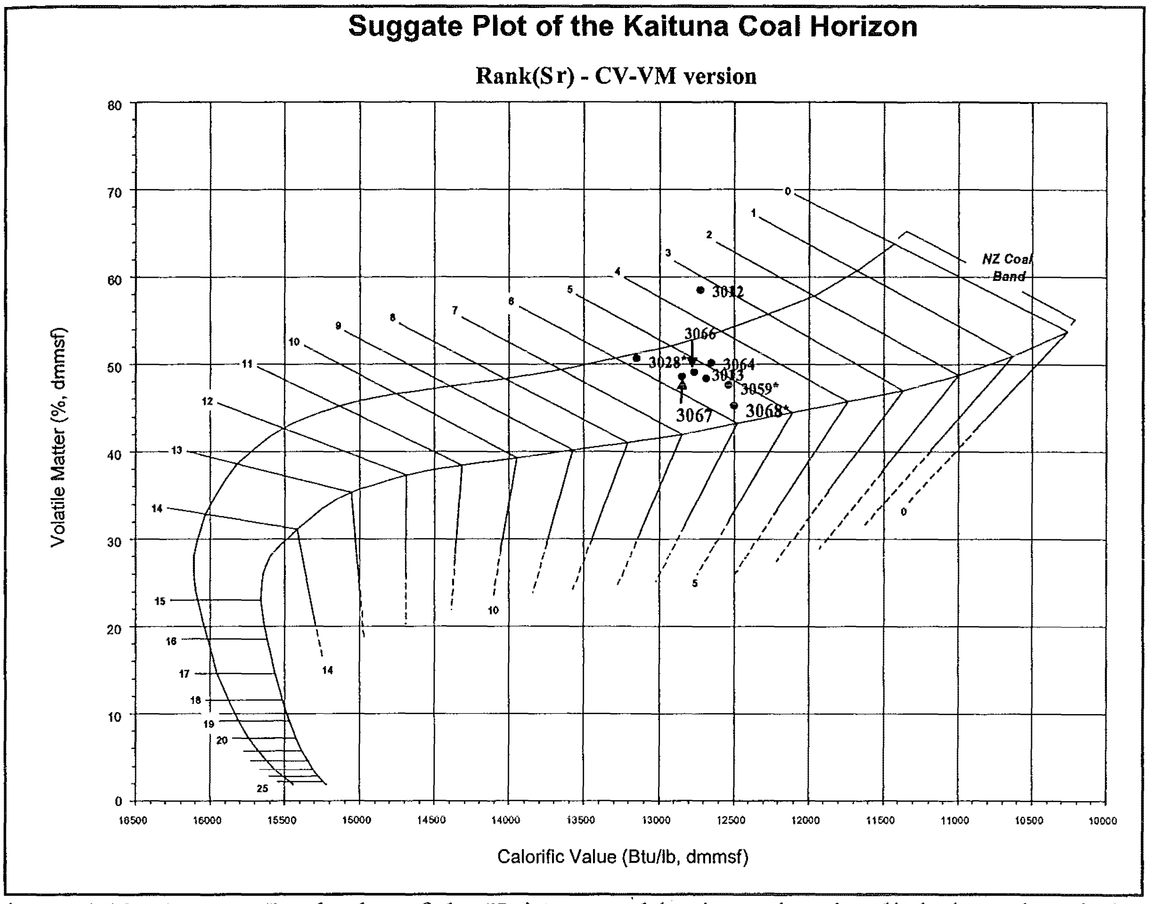


Figure 4.13: Suggate Rank plot of the Kaituna coal horizon showing little lateral variation, but more type variation. Drillholes with asterix symbols indicate high ash samples (see Appendix E)

4.2.2.6 Barclay Coal Horizon

The Barclay Member was the highest stratigraphic member sampled for VR in the Kaitangata Sector. VR samples were higher in the southeast of the coalfield, but sample coverage was inadequate to confirm this as a lateral rank trend. CV isopachs indicate two areas with high Btu/lb readings, in 3027 and 3056 to the east, and Kai Point Opencast, 3013, 3024 to the west (Figure 4.14). It is interesting to note the distribution of faults and volcanic intrusive relative to CV variation (4.15). A Suggate Rank plot was in agreement with CV isopached data showing an increase in rank in drillholes 3013, 3024 3027 and 3056. Suggate Rank supports high rank in drillholes 3013, 3024 and 3027 and shows very little rank variation in the rest of the Barclay coal horizon illustrating rank variation between 4.6 and 5.6 units for the rest of the Barclay coal horizon (Figure 4.16).

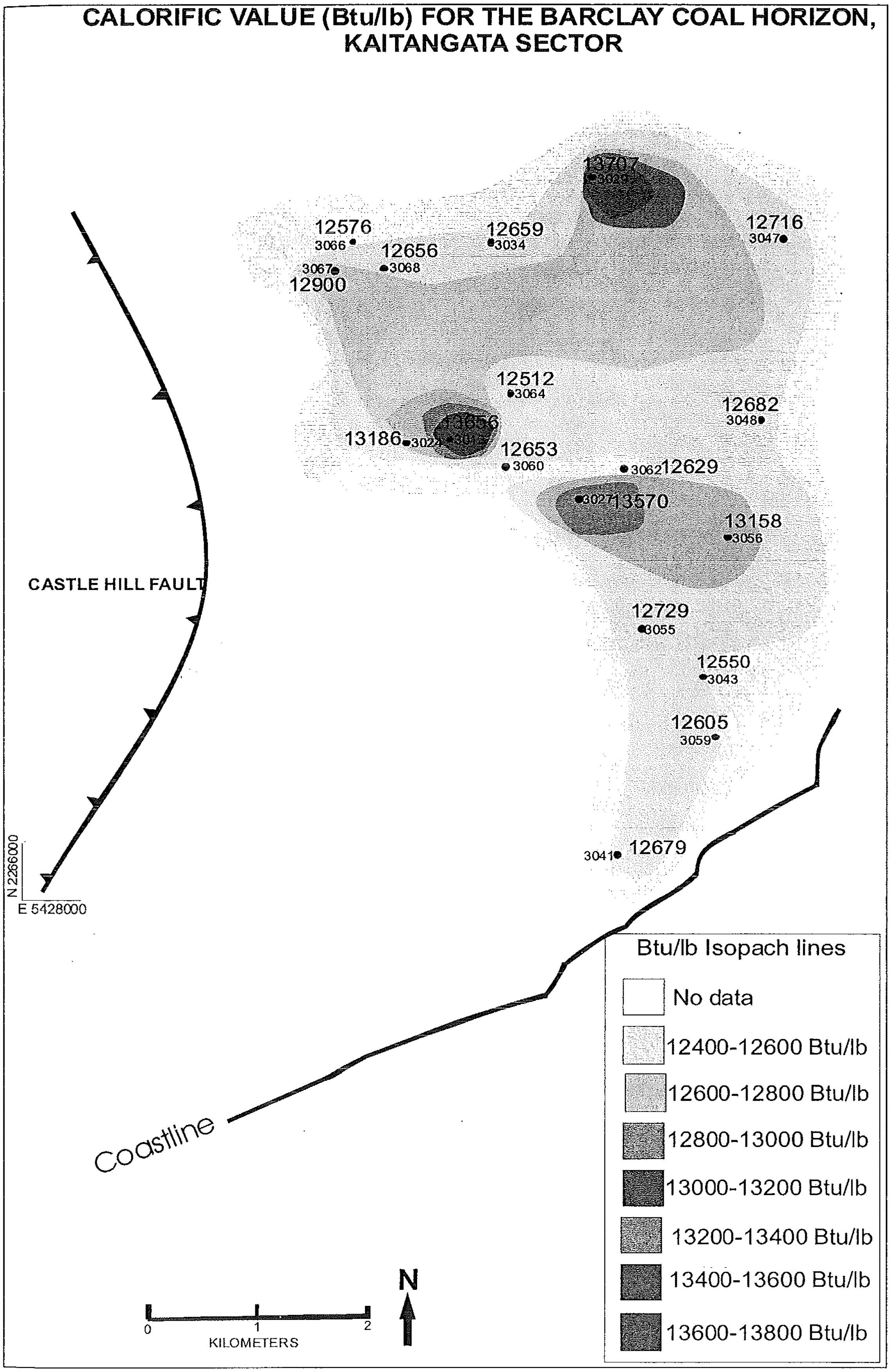


Figure 4.14: Calorific Value (CV) isopach map for the Barclay coal horizon.

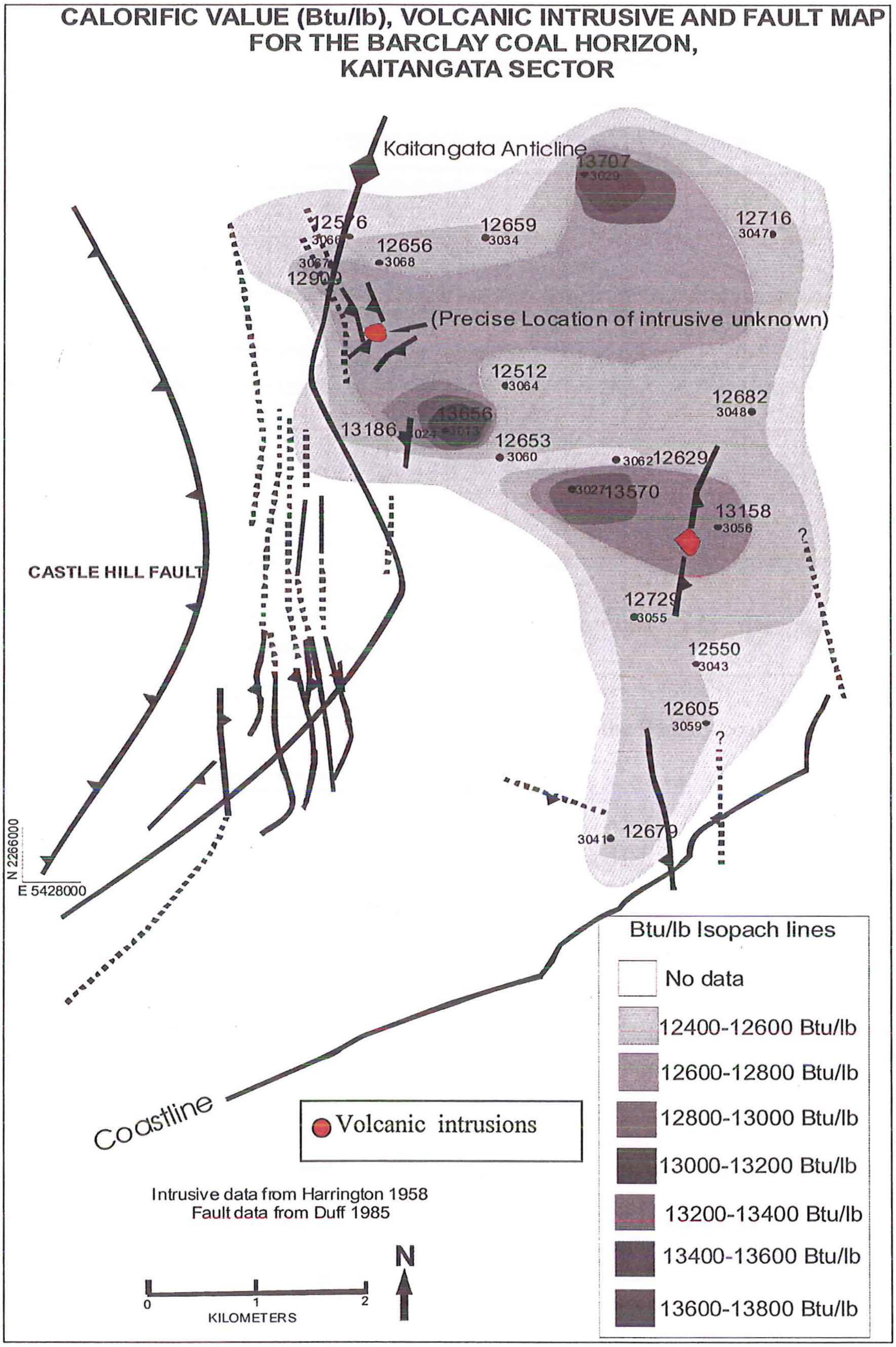


Figure 4.15: Location of known Miocene volcanic intrusions and faults relative to Calorific Value trends within the Barclay coal horizon.

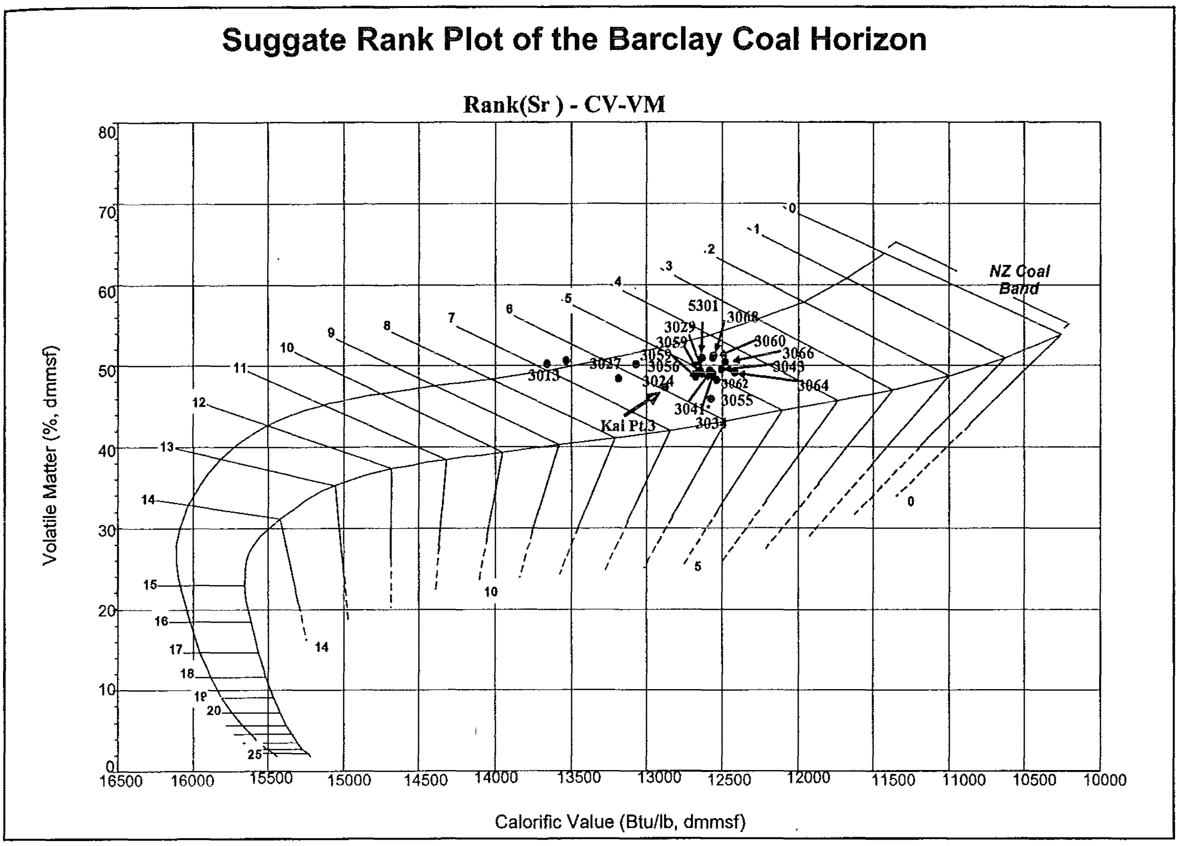


Figure 4.16: Suggate Rank plot of lateral rank variability in the Barclay coal horizon.

4.2.2.7 Washpool Coal Horizon

The Washpool coal horizon has two areas in which CV isopach data exists. Coal rank in drillholes 3023, 3033,3036 and 3068 have CV values between 12717 and 12842 Btu/lb. The other area approximately 3km to the southeast has three data points from drillholes 3043, 3056 and 3058, with CV values between 12669 and 12966 Btu/lb (Figure 4.17) these higher rank areas occur in similar areas to the those discussed in the Barclay coal horizon. Suggate Rank (Figure 4.18) does not support lateral CV trends and that indicates there is very little rank variation in the Washpool coal horizon with most samples falling within one Suggate Rank unit. Suggate Rank shows the Washpool coal horizon plots towards the top of the New Zealand coal band, indicating that the coal may be becoming perhydrous.

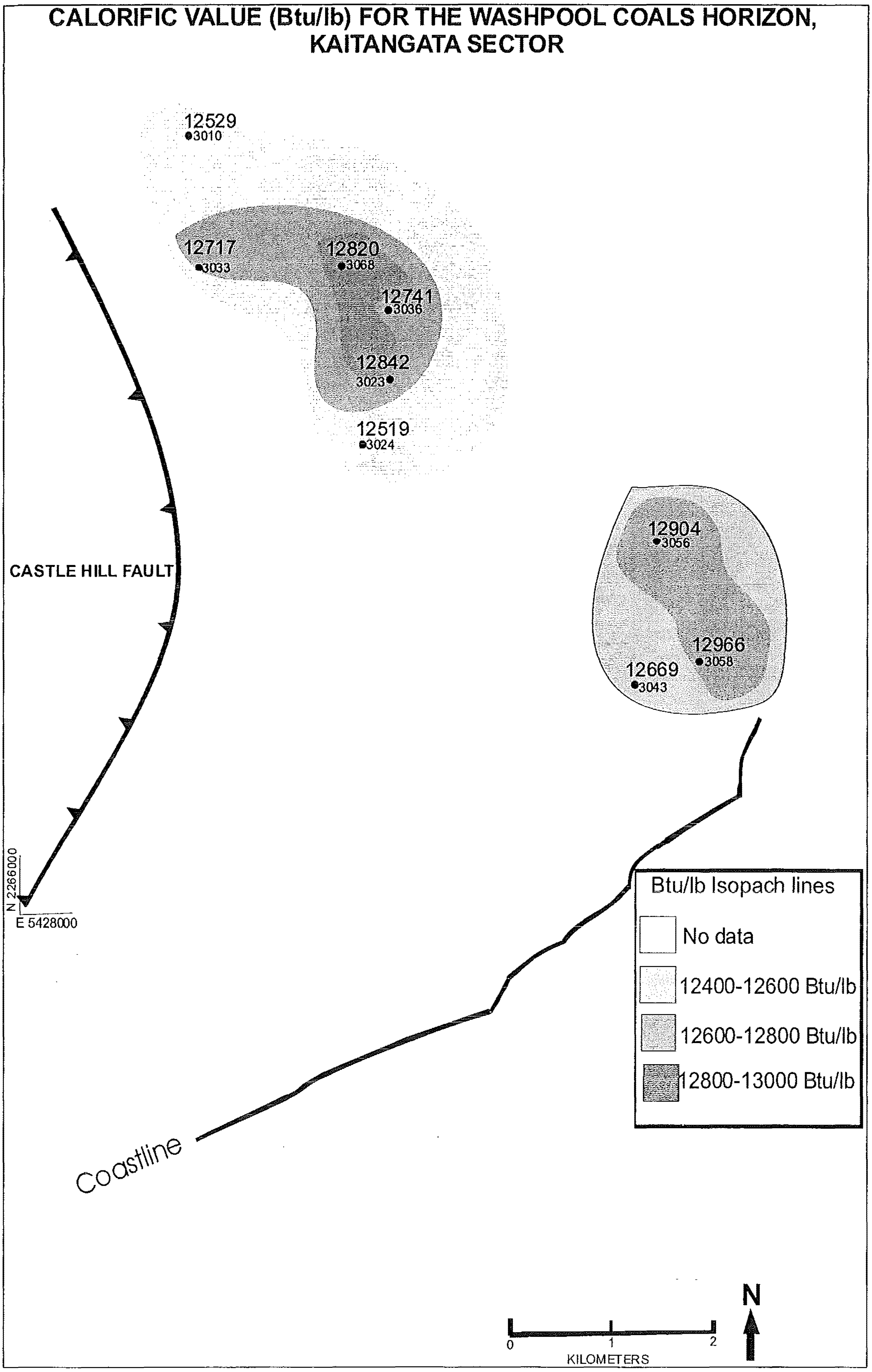


Figure 4.17: Calorific Value (CV) isopach map for the Washpool coal horizon.

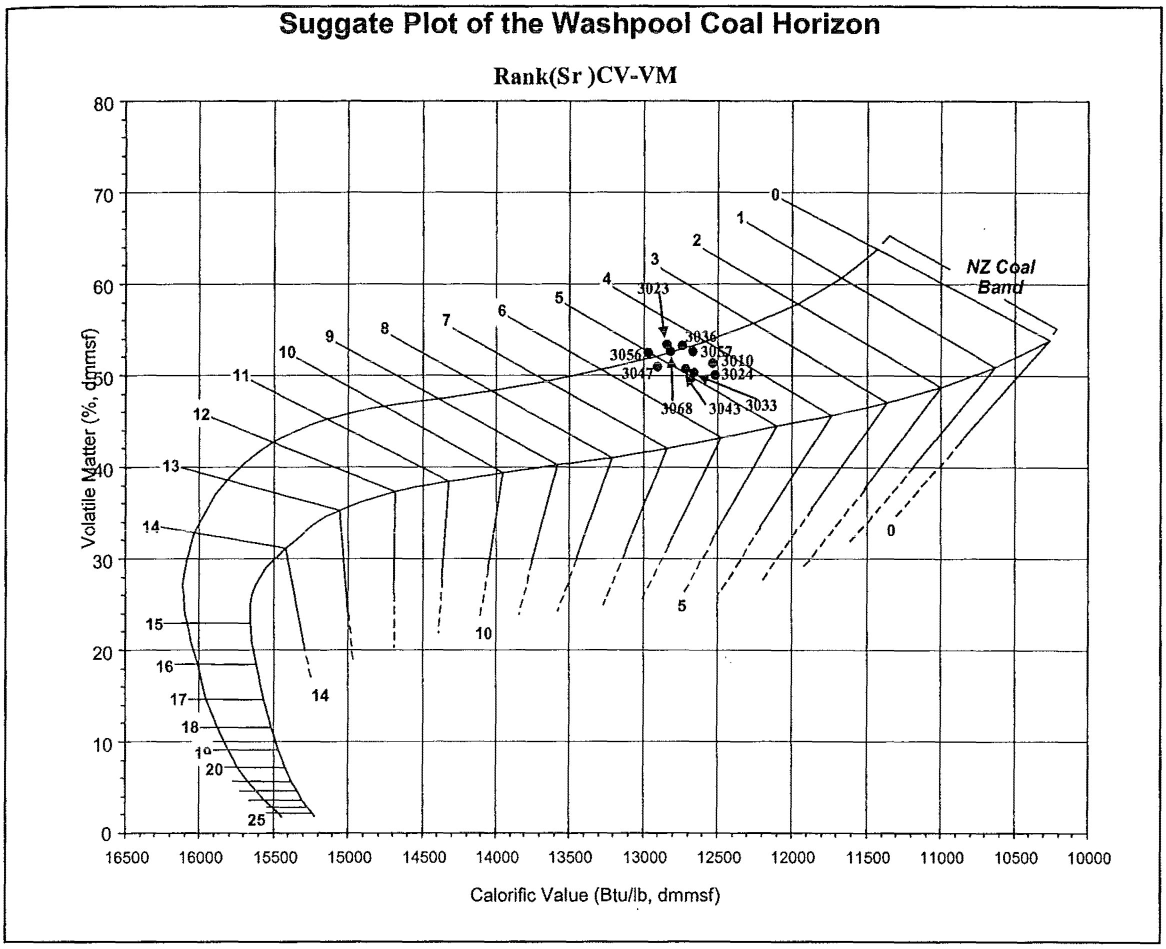


Figure 4.18: Suggate Rank plot of the Washpool coal horizon showing little lateral variability in rank.

4.2.3 Benhar Sector Downhole Rank Trends

Downhole rank trends in the Benhar Sector used VR and CV data from the Mount Wallace, Benhar, and Penman coal horizons. Insufficient data exists of the Coombe Hay coal horizon for it to be utilised in rank studies.

4.2.3.1 Drillhole 3050

Two intervals were analysed for VR in drillhole 3050. However, both readings from the Benhar and Penman Seams were both 0.33 R_{o}. CV of the Mount Wallace, Benhar and Penman coal horizons displayed a clear increase in rank with depth (Figure 4.19). CV showed an increase with depth from 11665 Btu/lb in the Mount Wallace Member to 12130

Btu/lb for the Benhar Member, and 12630 Btu/lb for the Penman Member. This equates to an increase in CV of 585.8 Btu/lb/100m.

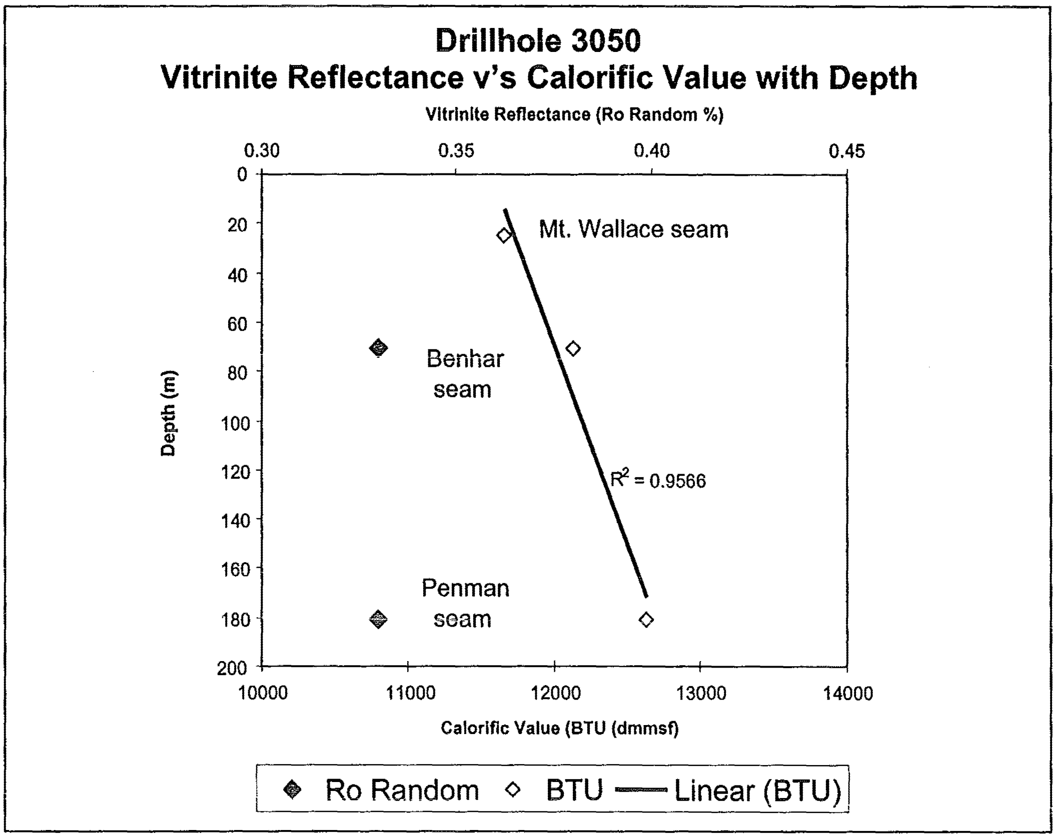


Figure 4.19: Comparison of downhole trends for drillhole 3050 between, vitrinite reflectance and calorific value with depth.

4.2.3.2 Drillhole 3052

Drillhole 3052 showed a linear increase in rank with depth for both VR and CV (Figure 4.20). VR increased from 0.30 to 0.33 R_0 from the Benhar to the Penman Members over a depth of 136.3 meters However, these analyses were within the error limit of VR, so therefore are regarded as a similar rank. A rank increase was distinguishable within CV, increasing from 12161 to 12642 Btu/lb over 136m, equating to a rank increase of 353 Btu/lb/100m.

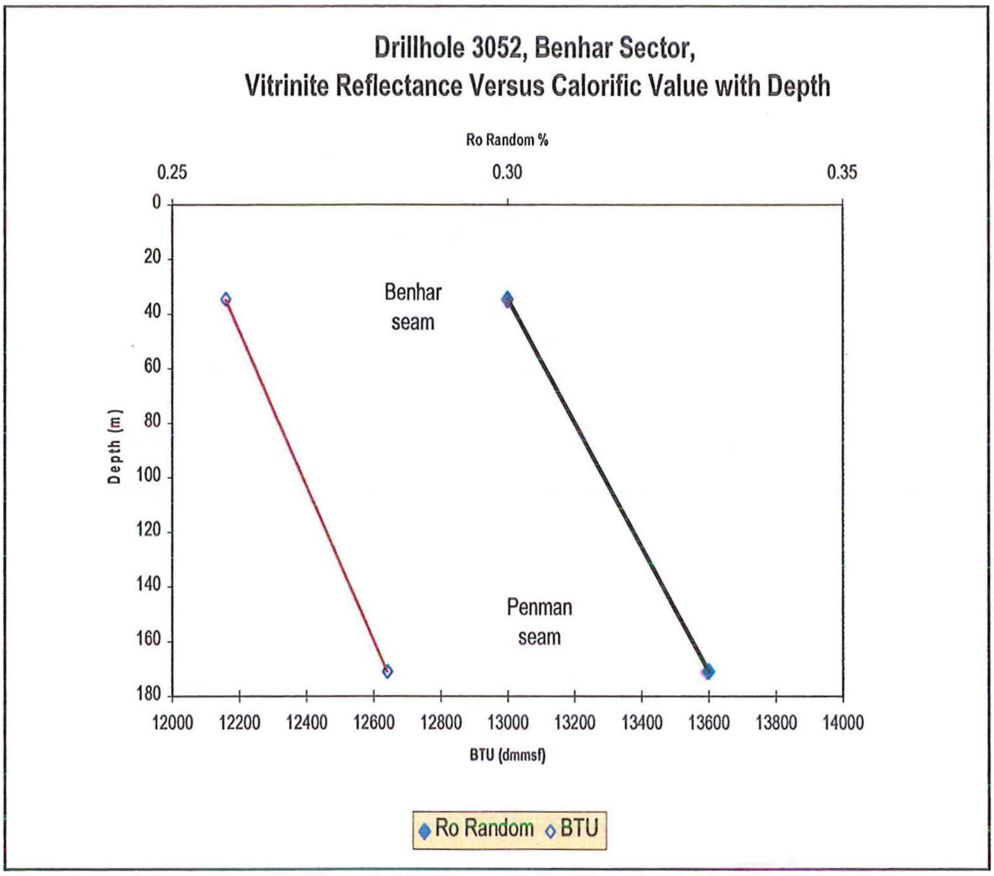


Figure 4.20: A comparison of down hole trends for drillhole 3052, between vitrinite reflectance and calorific value.

4.2.3.3 Other Members with Limited Data

Taratu Members with limited coal analytical data have been combined into a single Suggate Plot (Figure 4.21) so that at least some indication of coal rank values exists. This plot includes the Carson, Broome, Muir, Coombe Hay, and two unknown coals from Coal Gully, Tokoiti (far east of the Kaitangata Sector), and a coal sample from Aotere (sometimes called Akotere), located approximately 30km east of the coalfield.

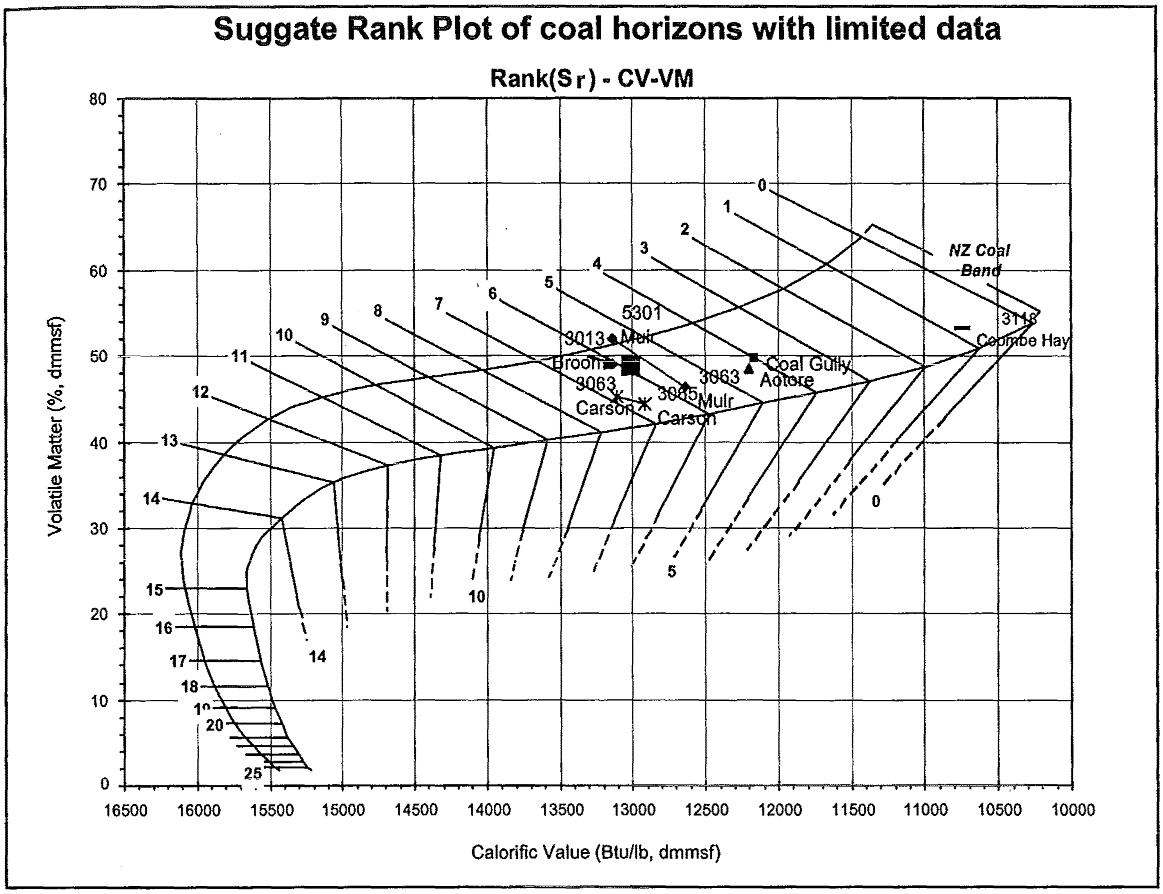


Figure 4.21: Combined plot of coals within insufficient data for trend analysis.

4.2.4 Lateral Rank Trends, Benhar Sector

Lateral rank trends were undertaken on the Mount Wallace, Benhar and Penman coal horizons. As only one sample exists for the Coombe Hay coal horizon lateral rank trends could not be analysed.

4.2.4.1 Penman Coal Horizon

Vitrinite reflectance measurements were completed on samples from drillholes 3052, 3050, 3046 and 3030. Reflectance readings were 0.33 R_o in most drillholes except for drillhole 3046, which had a reflectance reading of 0.35 R_o, All samples were within the error limits of VR and showed no lateral rank trends. Rank trends have been depicted using CV, which show a progressive increase in rank towards the Castle Hill Fault (Figure 4.22). Suggate Rank plots show a similar rank trend with values increasing from 4.7 to 6 S_r units as drillholes approach the fault zone (Figure 4.23).

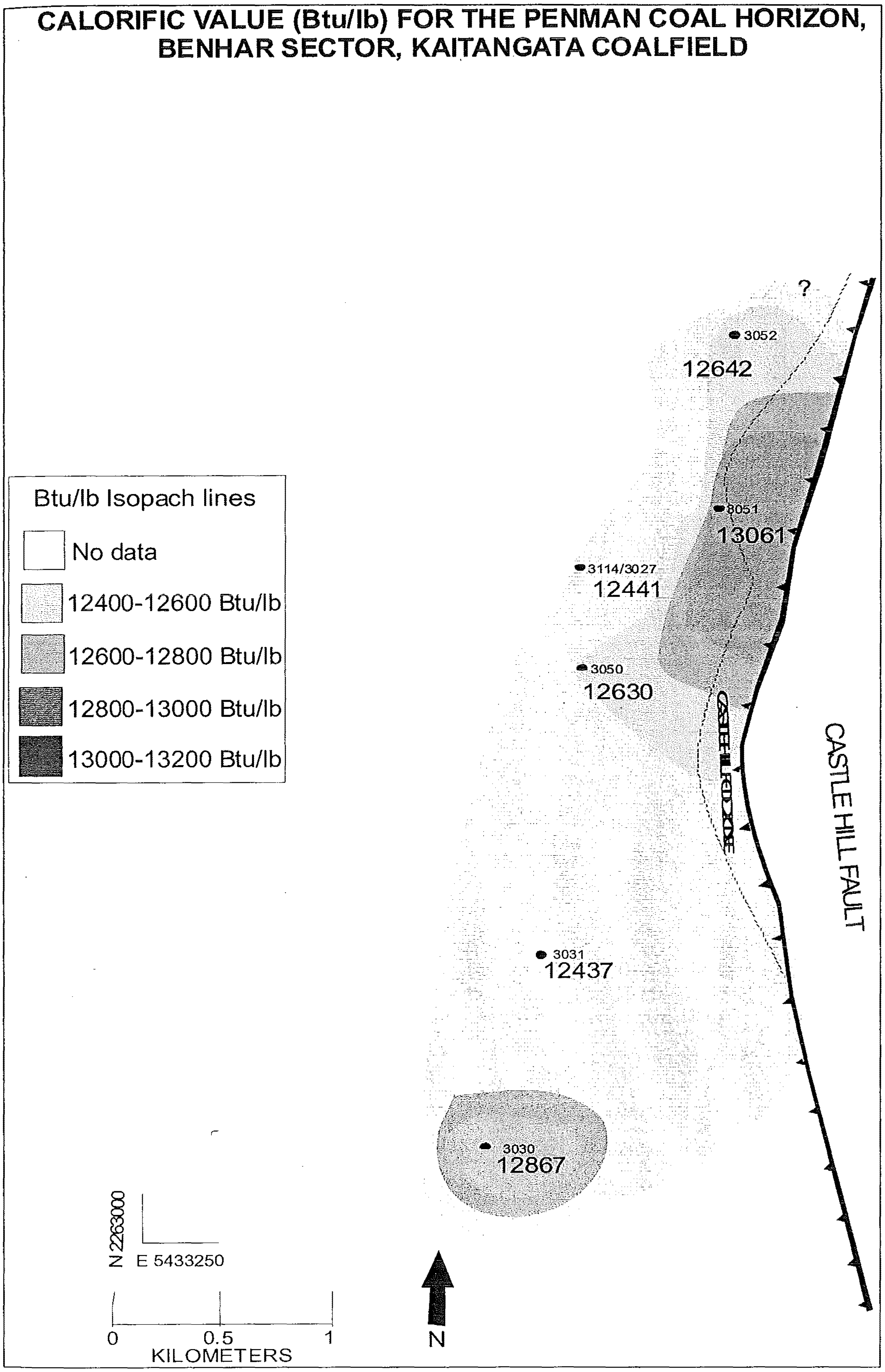


Figure 4.22: Calorific Value (CV) isopach map for the Penman coal horizon.

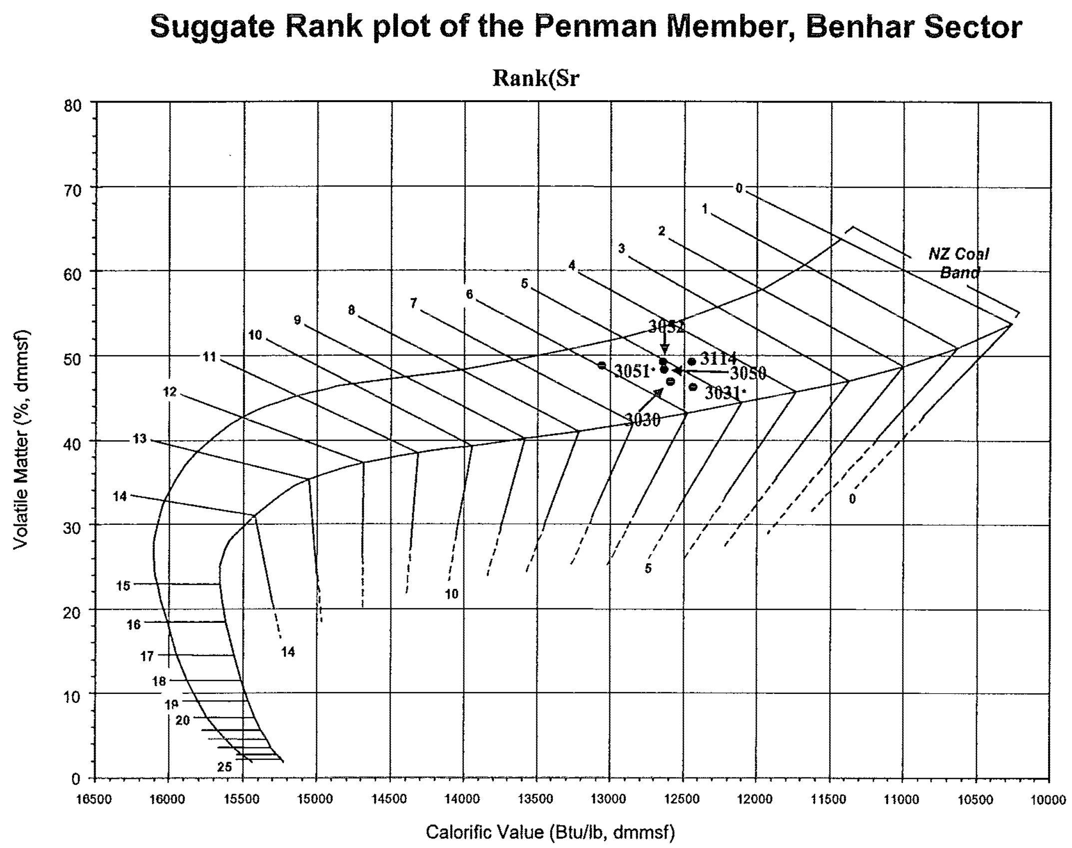


Figure 4.23: Suggate Rank plot of the Penman Coal Horizon showing little rank and type variability in the member.

4.2.4.2 Benhar Coal Horizon

The Benhar Main coal horizon is the most laterally extensive coal-bearing member in the Benhar Sector and samples were taken from outcrop and drillcore. The highest vitrinite reflectance reading was taken from the Elliotvale Opencast Mine (abandoned) which had a reflectance reading of 0.37 R_o, substantially higher than other samples collected in the Benhar Sector which range from 0.30 to 0.33 R_o. Like the Penman Member, the Benhar Member shows a lateral increase towards the Castle Hill Fault, with maximum Btu/lb values of 12535 and 12744 within 750m of the fault. Towards the south of the Benhar Sector there is also an area with high CV (Figure 4.24). Suggate Rank supports rank variation in the Benhar Member, however unlike the Penman coal horizon, this does not show a linear trend towards the fault zone (Figure 4.25).

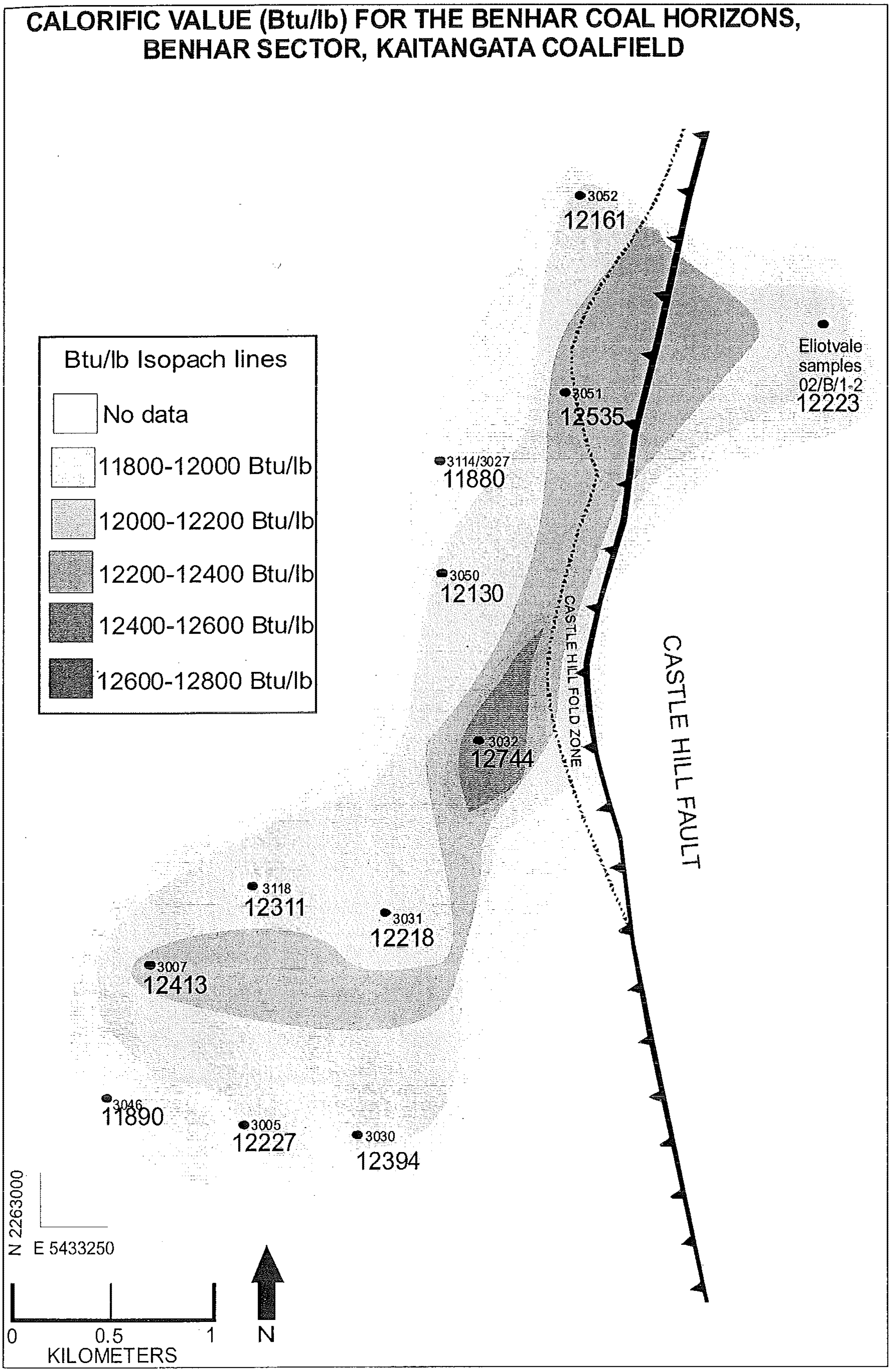


Figure 4.24: Calorific Value (CV) isopach map for the Benhar coal horizon.

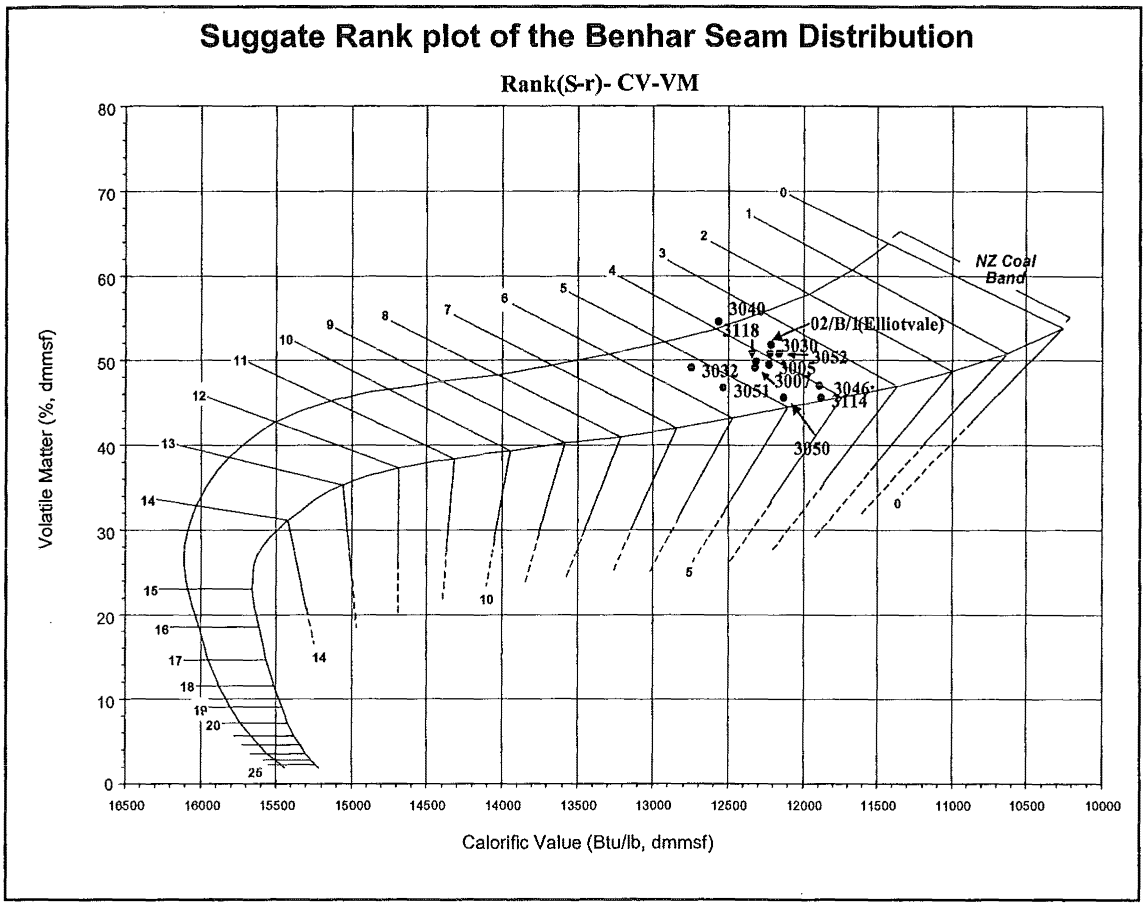


Figure 4.25: Suggate Rank plot of lateral and type variation in the Benhar coal horizon.

4.2.4.3 Mount Wallace Coal Horizon

Only one VR sample was completed on the Mount Wallace coal horizon, which had a low VR of 0.28 R_o. CV data provided lateral data coverage, like the other Benhar Sector coals, it showed a general rank increase towards the Castle Hill Fault. Similar to the Benhar coal horizon, CV in the Mount Wallace coals show an area to the south of the sector with elevated Btu/lb levels (Figure 4.26). Suggate Rank plots illustrate show rank variation within the member, but like the Benhar coal horizon there is not a linear trend towards the Castle Hill Fault (Figure 4.27).

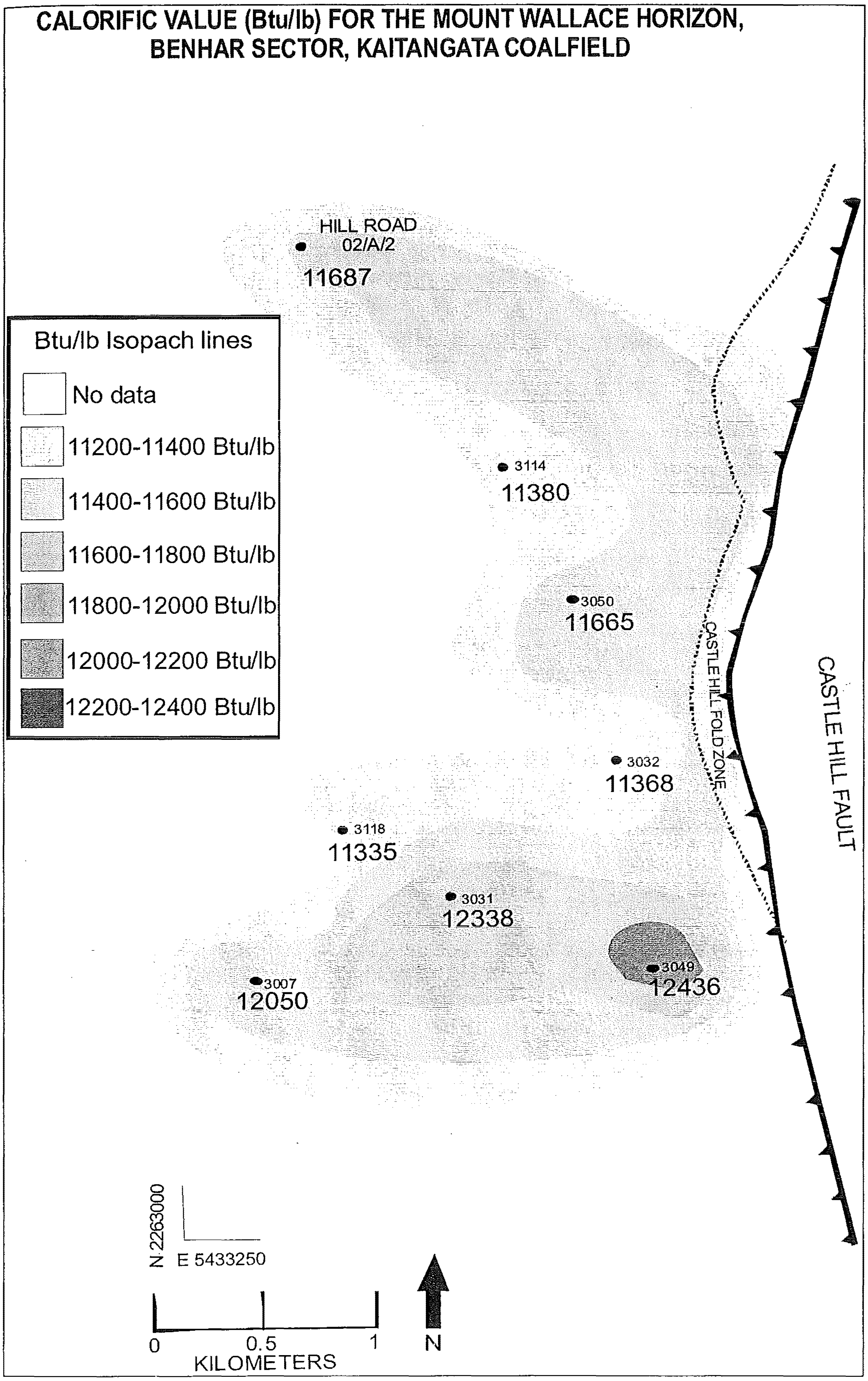


Figure 4.26: Calorific Value (CV) Isopach map for the Mount Wallace coal horizon.

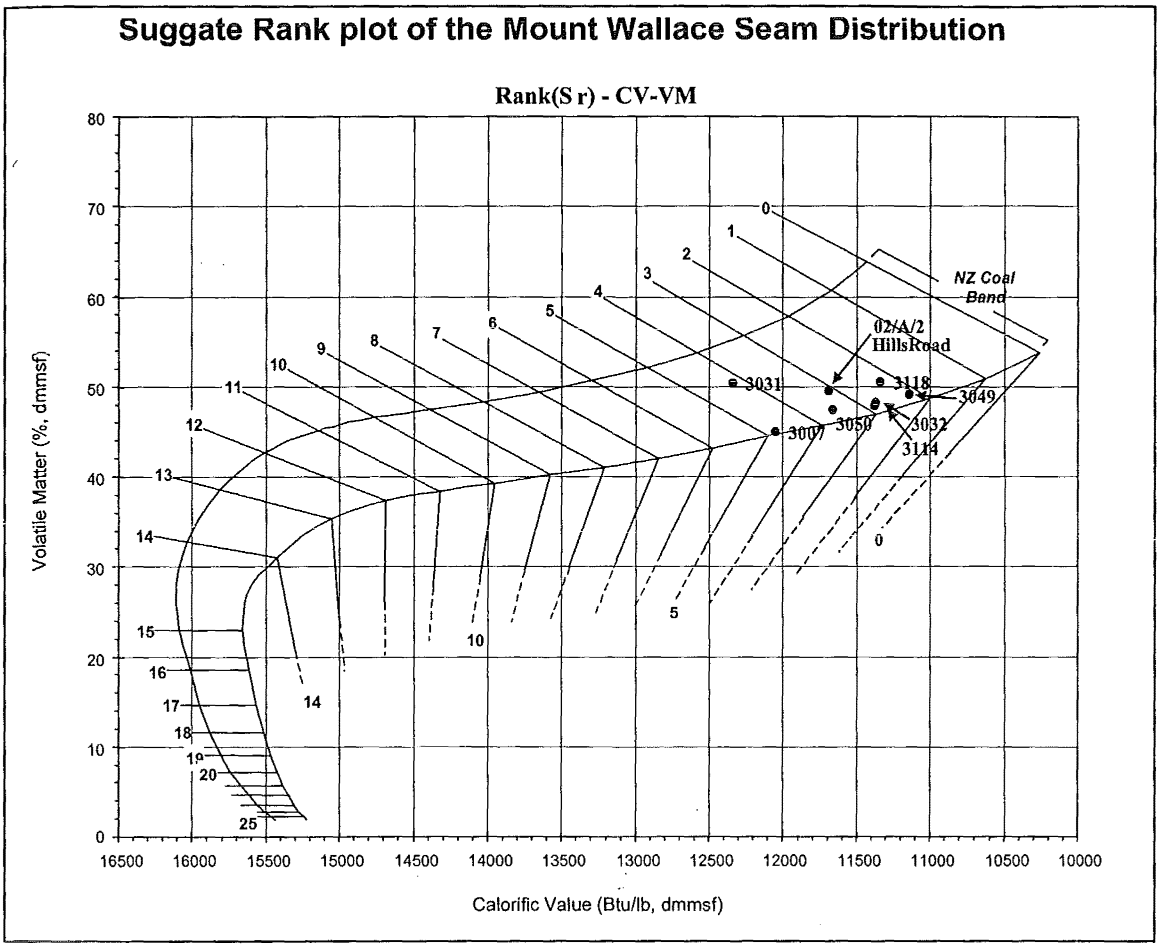


Figure 4.27: Suggate Rank plot of the Mount Wallace coal horizon showing rank and type variation.

4.2.4.4 Coombe Hay Coal Horizon

Only one CV data point with a value of 10743 has been obtained for the Coombe Hay seam, therefore no lateral trends could be attempted. Suggate Rank plots indicate very low values of 0.9 Suggate Rank units for this seam (Figure 4.21).

4.2.5 General Rank Trends

Samples that best represent different coal bearing members at certain stratigraphic levels were selected for a generalised Suggate Rank plot. These samples were chosen to best represent the average coal chemistry of members at different stratigraphic horizons for each sector of the coalfield. Generally, this shows that there is an increase in rank with depth stratigraphically, although some seams show rank variation, which may be not entirely due to purely the stratigraphic level of the coal. Such complications will be discussed in detail in section 4.2.7.

The Benhar Sector shows much more lateral variability across the rank spectrum, with coals plotting from 0.9 to almost 6 S_r units (Figure 4.28). In comparison, the Kaitangata Sector has a much tighter cluster of data covering 3.6 to 7.4 S_r units generally, showing an overall higher rank with less inconsistency in lateral variation (Figure 4.29).

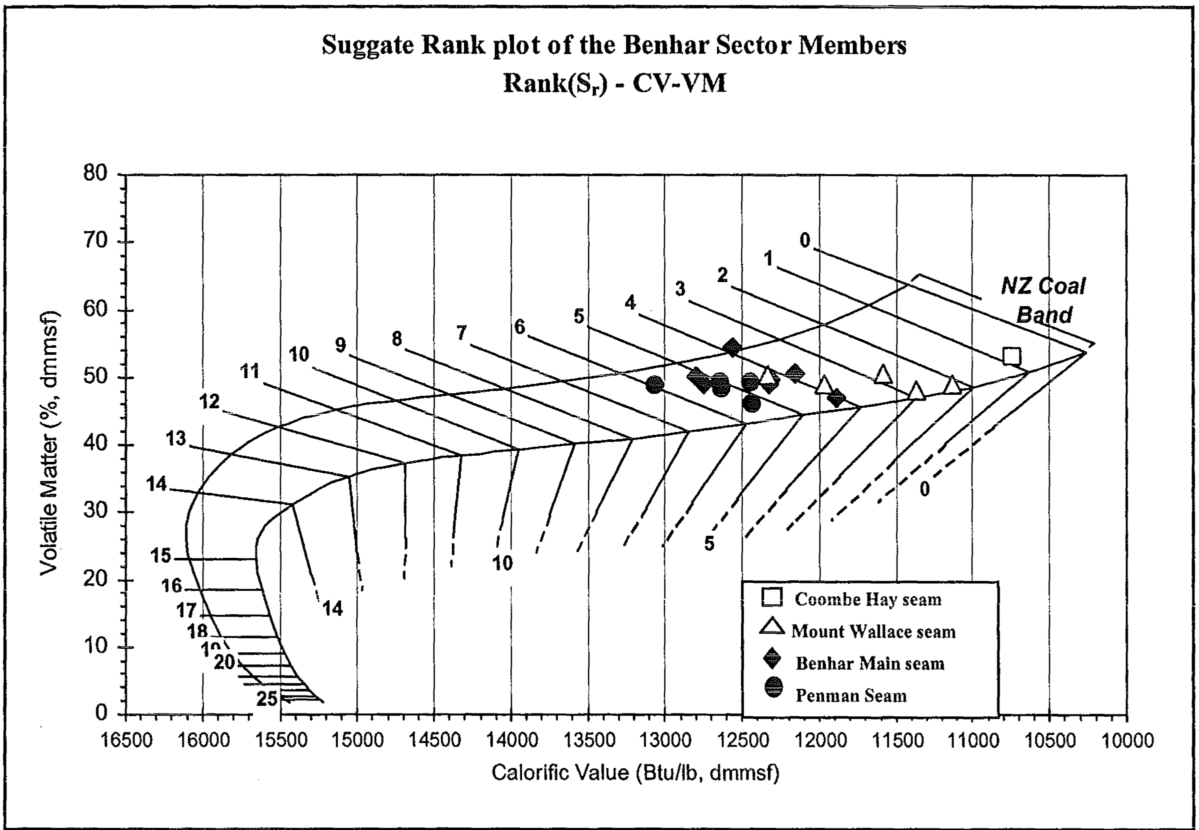


Figure 4.28: Suggate Rank plot of selected Benhar Sector coals, showing a stratigraphic increase in rank.

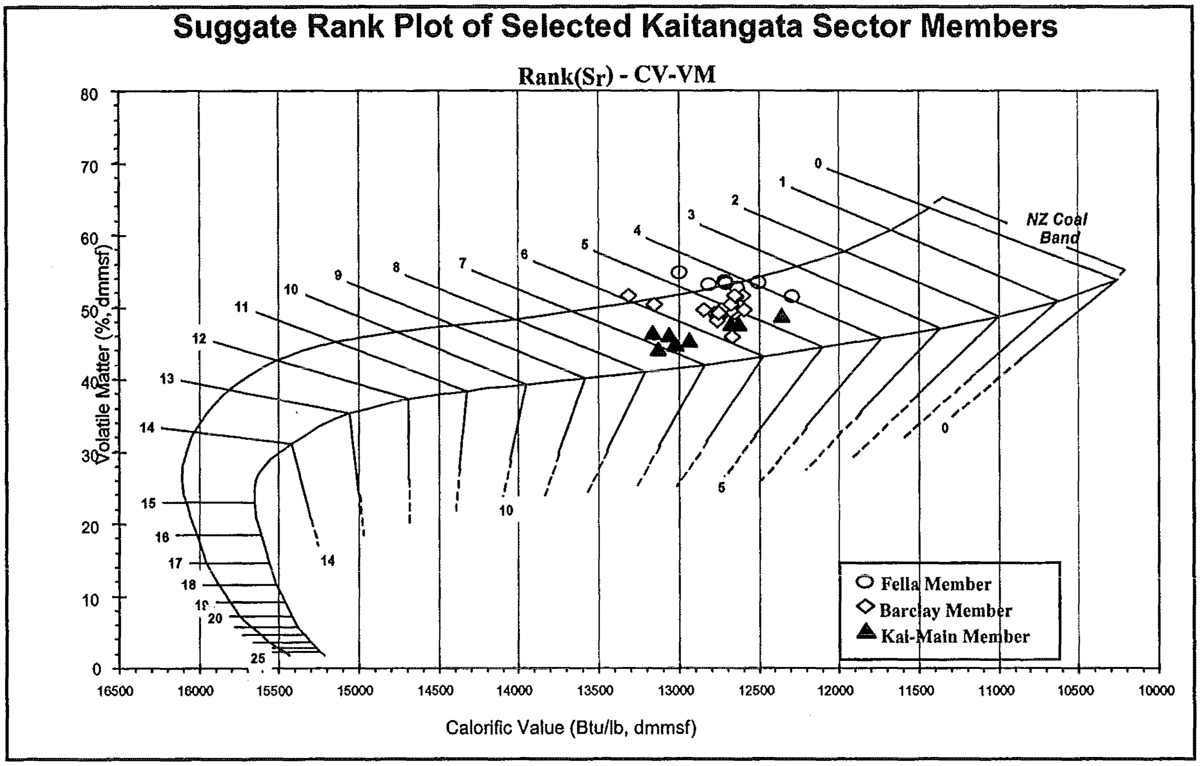


Figure 4.29: Suggate Rank Plot of selected Kaitangata Sector coals showing a stratigraphic increase in rank, but over less range than the Benhar Sector coals.

4.3 INTERPRETED THERMAL HISTORY

Understanding the thermal history of the Kaitangata Coalfield is important for recognising the timing and controls on coal maturation. The detection of vertical and lateral trends within coal bearing members will aid future coal exploration in the Kaitangata Coalfield. Firstly, the purpose of this section is to discuss the relative influence of parameters affecting the trends observed laterally and with depth across the Kaitangata Coalfield such as burial, faulting and volcanic intrusive, all of which have featured prominently over the geological evolution of the Kaitangata Coalfield. Secondly, this section will discuss complicating factors that may influence results, such as coal type and correction factors during coal chemistry analyses.

4.3.1 Causes of Downhole Rank Trends

Downhole rank trends from both the Kaitangata and Benhar Sectors of the coalfield showed a linear increase in coal rank with depth, e.g. drillhole 3064 (Figure 4.2) and drillhole 3052 (Figure 4.20). The overall rank attained with depth was higher in the Kaitangata Sector than the Benhar Sector. Rank within the Kaitangata Sector increased by an average of Ro 0.037/100m, whereas the Benhar Sector showed a negligible increase in Ro reflectance with depth, falling within the error limits of the vitrinite reflectance technique. However, calorific values (Btu/lb) provided better data reliability supporting an average linear downhole rank in the Benhar Sector of 469Btu/lb/100m, and a trend of 505Btu/lb/100m in the Kaitangata Sector, indicating that coal rank increases with depth generally across the entire stratigraphic range of the Taratu Formation.

4.3.1.1 Burial

The linear increase in rank with depth is best explained as a function of burial depth. The higher rank Kaitangata Sector, being older, would have received a greater degree of burial and a longer burial time than the Benhar Sector. This allowed for a greater rank to be attained with depth for the Lower and Middle Members, whereas, the effects of burial in the Benhar Sector was related to a later phase and underwent less burial.

The geothermal gradient of the Kaitangata Basin does not appear to have been very high over the geological history of the Kaitangata Coalfield, even during the emplacement of regional intrusives (i.e. the Miocene aged Dunedin Volcanic Group). An assessment of the maximum temperature of the basin using vitrinite reflectance readings attained from coal samples indicates that the Kaitangata Basin would not have exceeded temperatures between 50-80 °C over the ~65 million years of burial (Figure 4.30). This supports the premise that the degree of coalification experienced, and the rank obtained with depth, is primarily driven by burial depth in the basin with a low geothermal gradient.

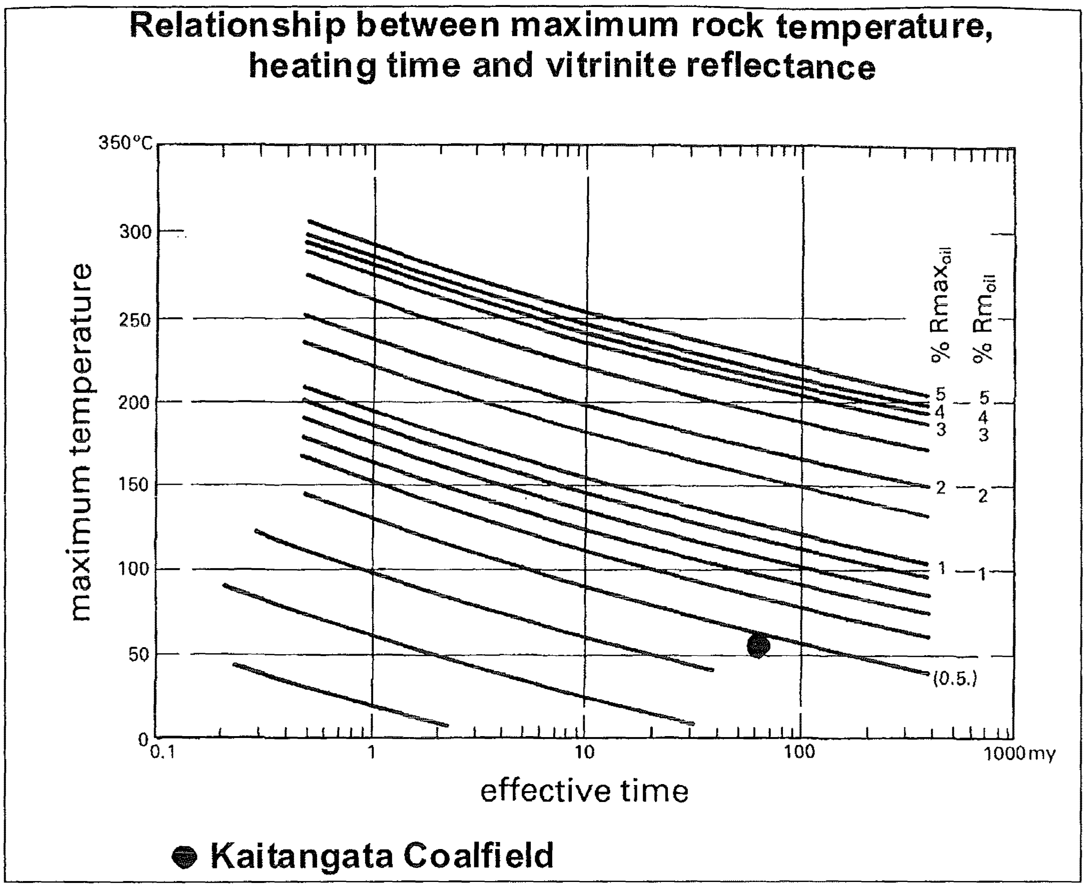


Figure 4.30: Maximum geothermal gradient of the Kaitangata Coalfield (After Bostick, *et al.*, 1979).

4.3.2 Causes of Lateral Rank Trends

Lateral rank trends in the Kaitangata coalfield could be attributed to three possible factors; burial, heat flow or volcanic intrusions. Lateral rank trends show the most obvious lateral variation in the Benhar Sector and in the Barclay coal horizon, Kaitangata Sector (Figures 4.15; 4.22; 4.24; 4.26). Unfortunately, the data density is sparse in Lower Taratu Members and therefore no obvious trends could be detected. However, Suggate Rank plots of the Capstick coal horizon suggest some lateral variability in the Member (Figure 4.11).

4.3.2.1 Burial

The coal thickness maps indicate that the Penman coal horizon increases in coal thickness towards the Castle Hill Fault (Appendix B). It is therefore possible that coals proximal to the Castle Hill Fault received more burial as the result of higher subsidence rates next to the fault than in the non-faulted Benhar Sector. Differential burial over the lateral distribution of the coal measures would mean that coals buried more deeply with a higher ratio of overburden, would be expected to reach higher ranks than laterally equivalent coals with lesser burial. This might account for the lateral trends shown in the Benhar Sector.

4.3.2.2 Fluid Flow along Faults

Fluid flow along faults may have provided a localised increase in the geothermal gradient increasing the rank of coals proximal to the fault boundary. The Kaitangata Coalfield has been exposed to both syn and post-depositional fault development, both of which may have influenced the properties of different coal members to some degree.

Syndepositional faulting along the Castle Hill Fault essentially controlled the distribution and thickness of coals, especially during the deposition of the Lower and Middle Taratu coal horizons. Whereas, during the Upper Taratu times coal distribution and thickness is the result of regionally controlled subsidence framework. It is hard to separate the different influences on rank, such as syndepositional faulting as a single influence Nevertheless, the basins depositional history is by no means this simple. Post depositional faulting may have also had an influence. Miocene faulting which caused the development of the Kaitangata Anticline in the Kaitangata Sector and the development of a numerous normal, reverse and thrust faults.

High heat flow along the Castle Hill Fault may have assisted with coal maturation proximal to the fault boundary. However, it would be expected that a concentric decay in maturation levels away from the fault would be evident (Teichmüller, *et al.*, 1998). This does not appear to be the case, so it is more likely that maturation is primarily driven by burial with perhaps a minor component of high heat flow.

4.3.2.3 Volcanic Intrusives

The Miocene Dunedin Volcanic Group commonly intruded along older faults and crustal weaknesses, which in South Otago, are often Cretaceous in age. Data from the Barclay coal horizon indicate that secondary rank enhancement may have occurred as the result of the Miocene aged volcanic intrusions. CV and Suggate rank supports two areas of high rank near drillholes 3013 and 3027 in areas proximal to known intrusions (Figures 4.14 to 4.16). The most northerly intrusion was reported as a dyke of up to 25 meters across and 360 meters in length in mine workings of the Taratu Mine (Ongley, 1939). However, very little information is known about the other intrusion to the southeast apart from it being mapped by Ongley (1939). The strike of the northern most intrusion is not sufficiently detailed, so further inferences of whether these two intrusives are the same dyke, or if they are isolated intrusions cannot be made. It is hereby suggested that in intrusives may have had a localised effect on coal rank within the Kaitangata Coalfield with localised volcanic intrusives intruding along faults and joints related to pre-existing weaknesses and joints such as faults and deformation structures.

4.3.3 Sources of Unexplained Variation

Localised increases in rank vertically and laterally may be related to other factors. They could be genuine rank increases from thermal causes, but there is also the probability that they are related to errors resulting from analytical methods and assumptions, especially when there is a fine margin between error limits and data variability.

4.3.3.1 Coal Type Variation

One of the most important considerations for error is coal type variation. This is particularly important when considering perhydrous coals for VR analysis.

The use of Suggate Rank plots showed that the upper Middle Taratu Members, especially the Washpool Member, plot very high in the New Zealand coal band (Figure 4.18). This indicates a perhydrous component to the coals (Suggate 1959).

Perhydrous coal can be formed as the result of a number of factors. Coals that originate from hydrogen rich plant types will exhibit perhydrous coal chemistry (Stach, *et al.* 1984). In addition, perhydrous coals occur from sulphate-rich conditions in the depositional environment or early post-depositional percolation of marine waters into coals during a transgression (Diesel, 1994). There is strong evidence for syndepositonal marine influence for the upper Middle Taratu Members; this would have allowed sulphate and hydrogen enrichment during coal deposition. Perhydrous coals are known to suppress vitrinite reflectance values and maybe a source of error for rank assessment using VR on the Middle and Upper Taratu Members.

Vitrinite and Inertinite Reflectance (VIRF) analyses carried out Kaitangata coals did not find a significant perhydrous element to coals (see Appendix D). However, it is thought that the current low rank of these lignites that perhydrous vitrinites are complicated by the coals chemistry. This is evident from the rapid transition between vitrinite and other coal submacerals such as semifusinite, and that with further coalification would show a more distinct perhydrous component.

4.3.3.2 Maceral Identification and the use of Telovitrinite

Telovitrinite shows a rapid transition to semifusinite and liptinite in some samples and this may be a source of error in some VR measurements. However, all samples all fell within the accepted error limits of 0.05 R_o for the vitrinite reflectance technique, which therefore minimise the probability of this error having an effect on results.

4.3.3.3 Coal Chemistry

Coal chemistry relies on a number of corrections and adjustments from the initial stages of laboratory testing to evaluating the final calorific values and volatile matter values. The correction factors used to attain the dry, ash, mineral matter, sulphur free basis for CV and VM comparison. Suggate Rank trends required some assumptions on coal constituents used in corrections.

In correcting CV and VM for ash, Suggate (1959) suggests an average correction factor of 1.10, based on analysis of ash constituents in New Zealand coals. However, ash constituents vary not only by coalfield, but also internally within a given coalfield. This may have ramifications for the Kaitangata Coalfield as the lithological facies coeval with different coal seams has varied in composition over the depositional history of the basin. Thus, the greywacke clast rich Lower Taratu Members may require a different correction factor than the quartz and clay rich Middle and Upper Taratu Members. Unfortunately investigating and constructing a basin and Member specific correction factor for ash was outside of the scope of this thesis and correction factors for ash relied on Suggate's (1959) averaged correction factor.

New Zealand coals in almost all cased have higher organic sulphur with lesser quantities of pyritic and sulphate sulphur (Suggate, 2000). In correcting for sulphur, it is assumed that the primary form of sulphur in coals are organic. This appears to be mostly true, but in some areas the amount of organic to pyritic and sulphate sulphur may differ as the result of different depositional environments. In this case, a generalised sulphur factor may provide sources of error if used to represent sulphur for all 16 coal members.

4.3.4 Synthesis of Thermal History

Differential rank trends seen in the Kaitangata Coalfield reflect a variable basin history. It appears that burial depth has been the most influential factor on coal rank with the most deeply buried Taratu Members showing higher ranks compared to the shallower Middle and Upper Taratu Members. The rank attained by the most deeply buried coals indicates that the maximum geothermal gradient experienced by coals would not have exceeded 80°C over the ~65 million years of burial.

The influence of the Dunedin Volcanics igneous intrusions is poorly understood. Although localised increases in rank near intrusions (e.g. Barclay coal horizon) may explain other increases in rank in the southern Kaitangata Sector.

The increases in rank observed in the Benhar Sector are probably due to fluid flow from the Castle Hill Fault. However, burial is also a viable option to explain rank trends.

CHAPTER FIVE

BASIN OVERVIEW

5.1 INTRODUCTION

The purpose of this chapter is to summarise the findings of this thesis regarding the evolution of the Kaitangata Coalfield in context with both the regional and New Zealand tectonic setting. Firstly, it is necessary to introduce background characteristics of rift and passive margin basin dynamics and provide an overview of the New Zealand mid Cretaceous-early Paleocene tectonics. This will allow the Kaitangata Coalfield's basin evolution to be discussed relative to large-scale events such as rifting and passive margin tectonic regimes. Secondly, a comparison will be made between the Kaitangata Coalfield and the Pakawau sub-basin (Taranaki Basin) to evaluate controls on the Late Cretaceous basin evolution.

5.1.1 Background: Mid-Cretaceous Rifting

Significant changes were taking place in the configuration and position of the New Zealand continental landmass just prior to the formation of the Kaitangata Basin in the Mid-Late Cretaceous. New Zealand underwent a very long period of convergence, terrane amalgamation, metamorphism, erosion and plutonism, from the Permian-Early Cretaceous (Laird, 1993). In the mid Cretaceous, the tectonic regime underwent a rapid change from convergent tectonics to divergent and extensional tectonics (Balance, 1993).

Three main phases of rifting have been identified by Laird (1993). The first period occurred in the mid-Albian (mid-Cretaceous). Intra-continental rift complexes oriented in the direction of maximum extension, north-northeast. Fault bound basins, such as the Great South Basin (GSB) complex formed in this orientation (Carter, 1988; Laird 1993; Cook, 1998). This north-northeast dominated extension caused the formation of large en-echelon normal faults with throws of up to 3000m, which were intermittently active during different pulses of rifting (Cook *et al.* 1998). During this time of rifting of New Zealand from the Gondwanan margin, the remnant influence of the convergent tectonics was still in effect. Inherited characteristics of convergent tectonic regimes, such as crustal thickening, granite emplacement and volcanism, left topographic remnants, related to rapid uplift, and crustal buoyancy of the New Zealand continental landmass (Laird, 1993).

The second phase of extension is thought to have resulted in continental break-up of New Zealand from the Gondwanan margin (Laird, 1993; Bradshaw, *et al.* 1996). The extension direction during this phase was oriented northeast-southwest occurring from the Late Albian-Early Cenomanian (Laird, 1993), resulting in uplift and the exposure of older New Zealand basement to extensive weathering (Williams, 1974). The weathering and subsequent erosion of exposed basement material from topographic paleohighs and fault scarps provided basin fill for these newly forming rift basins. Many intraplate volcanic events have been attributed to this stage, such as the Mandamus Igneous Complex, dated at 97 ± 0.5Ma (Weaver and Pankhurst, 1991), and the Mt. Somers Volcanics dated as 97Ma (Tapperden, *et al* 2002).

The third stage of rifting is recognised by the opening of the Tasman Sea. This is dated at 84-82 Ma by the appearance of rift-generated oceanic crust (Laird, 1993). This change is recognised by a change to mid–oceanic rift and a passive continental margin in New Zealand. Sedimentary deposits resulting from this change to passive margin tectonics can be recognised by widespread deposition of coal measures, glauconitic sandstones and limestones (Laird, 1993).

Causal mechanisms and tectonic reconstructions associated with continental rifting of the New Zealand-Antarctic-Australian margins are difficult to interpret, but there seems to be a fundamental relationship between the termination of subduction and the initiation of rifting. This can be seen in the complex relationship and subsequent overlap between the compressional and extensional tectonic signatures. For example, the Hohonu Batholith (109-114 Ma) on the Western Province of New Zealand shows geochemical traits of subduction-related melt but has shear fabrics and detachment surfaces indicating emplacement in an extensional tectonic regime (Tullock and Kimbrough, 1989). Complications further arise when placing age constraints on rifting events due to rifting occurring during the Cretaceous long-normal magnetic period, which reduced the diversity of magntostratigraphic data. Further restrictions are imposed by post-depositional/deformational processes, due to the initiation of the current Indian-Pacific plate boundary in the Neogene (Bradshaw, *et al.* 1996).

5.1.2 Characterising the Kaitangata Basin

The Kaitangata Coalfield is separated into two sectors, the Kaitangata Sector and the Benhar Sector separated by the Castle Hill Fault. The Castle Hill Fault is the onshore continuation of rift related faults from the Great South Basin rift complex, which was active during the separation of New Zealand from Gondwana in the mid Cretaceous. The Great South Basin is an intra-continental rift system with numerous sub-basins that are bound on three sides by basement highs, with the fourth side connecting the Great South Basin to the Canterbury Basin (Cook, *et al.* 1998). The Castle Hill Fault is considered an extension of either the Titri or Tuapeka faults, which are the most western faults of the Great South Basin boundary (Figure 1.2). Lindqvist (1998) correlates the Castle Hill Fault to be part of the Titri Fault, whereas Bishop and Turnbull (1996) infers the Tuapeka Fault to continue to the Castle Hill Fault. Either way, the Castle Hill Fault would have been a major basin bounding fault in the onland extension of the Great South Basin, the Kaitangata Basin.

Regionally the Taratu Formation succession is described in localities such as Shag Point and Dunedin as a passive margin deposit in which coal were deposited during thermal relaxation of the New Zealand continent (Diesel, 1992; Lindqvist, 1998). Many authors have noted that in the Kaitangata Coalfield, passive margin deposition is not a single event and that the transition from terrestrial strata to marine is more complex and significant local transgressions and regressions occurred before marine conditions prevailed in the Early Paleocene (Barry, 1985; Lindqvist and Douglas, 1987; Lindqvist, 1998). In addition, numerous authors working on the Kaitangata Coalfield have mentioned syn-depositional activity of Castle Hill fault during coal measure deposition (Raymond, 1985; Duff, 1985; Browne, 1986; Duff and Barry, 1989; Lindqvist, 1998), although none of the above authors have characterised the basin as a rift basin based on fault activity.

The Kaitangata Coalfield shows features of a rift basin. The north-south trending Castle Hill Fault provides a border fault, which joins the Kaitangata sub-basin onto a larger regional fault system related to the Great South Basin rift complex. The Titri Fault, like many mid-Cretaceous faults, has a northeast-southwest orientation. South of Milton at the southern end of the Taieri plains depression, the Titri Fault is thought to splay into several segments that have variable orientations such as the Castle Hill Fault (north-south) and the Tokomairiro Fault (northwest-southeast). Raymond (1985) suggested that the Tokomairiro Fault could be a continuation of the Tuapeka Fault due to its orientation, whereas the Castle Hill Fault is probably a continuation of the Titri Fault. This study considers the Kaitangata Coalfield to be directly influenced by both these fault systems, as well as distally affected by other regional faults such as the Livingstone Fault, which separates the Caples Terrane from Dun Mountain (Maitai Terrane) and Murihiku terrane to the southwest of the Kaitangata Coalfield. The importance of the Livingstone Fault has not been discussed in context to the Kaitangata Coalfield. However, it is noted by Carter (1988) that offset on this fault during the Late Cretaceous was up to several hundreds of meters. Carter (1988) further notes that during the Late Cretaceous movement on the Livingstone Fault, unlike most other regional faults that were normal, was reverse, which would have had consequences for the Kaitangata Coalfield.

5.1.3 Introduction to Rift Basin Models

The mechanisms involved in formation and development of the Kaitangata Coalfield span the initiation of a divergent plate margin and rifting from the mid-late Cretaceous, to post-rifting subsidence and passive margin development in the late Cretaceous-Early Paleocene (Ballance, 1993; Laird, 1993 Lindqvist, 1998).The Kaitangata Coalfield is best described as a rift basin as the inherent basin morphology is controlled by syn and post rift phases of basin development.

Continental rift basins have been the focus of substantial interest primarily due to their high preservation potential and economically significant deposits such as oil and gas (Miall, 1993). Rifts can form in a variety of tectonic settings (Sengör, 1995), but are most common in divergent plate tectonic settings (Boggs, 2001). Generally, there are two main types of rifts, active rifts, which are generated from mantle processes, and passive rifts which are initiated by lithospheric processes (Figure 5.1) (Frostick and Steele, 1993).

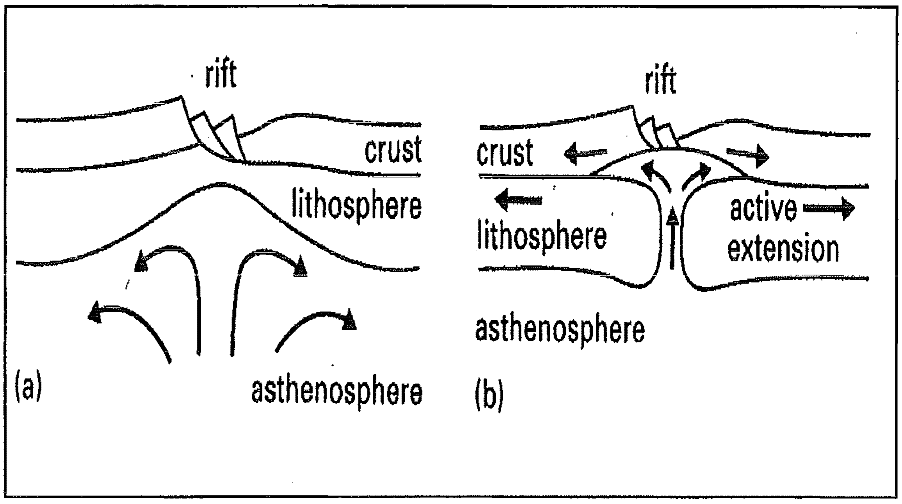


Figure 5.1: A comparison between, (a) a mantle generated rift and (b) a lithospheric generated rift (Turcotte and Emerman, 1983).

Mantle generated rifts are the result of regional doming and uplift due to the presence of mantle plumes or hot spot volcanism, which means they do not necessarily need to occur in an extensional tectonic setting (Frostick and Reid, 1989). These types of rifts are characterised by early and extensive volcanism, doming of crust causing river diversion, and high heat flow. Deposits in this type of setting are variable, but are usually distinguished by unconformities and volcaniclastic deposits, and a lack of clastic sediment supply (Cox, 1989; Frostick and Reid, 1989).

Rifting initiated by lithospheric processes, unlike mantle generated rifts, usually causes crustal thinning, creating depressions which attract river drainage and clastic sediment supply. Volcanism is usually late in the rifting process and if so, is usually sparse (Frostick and Steel 1993).

Rift basins of either type are typically half graben structures contrary to previous models, which had them as full grabens (Gibbs, 1984; Rosendhal, 1987). These basins are characterised by a single master normal fault (border fault) which controls the depositional framework for the basin. The main depocenter is asymmetrically located close to the master normal fault (Frostick and Steel, 1993).

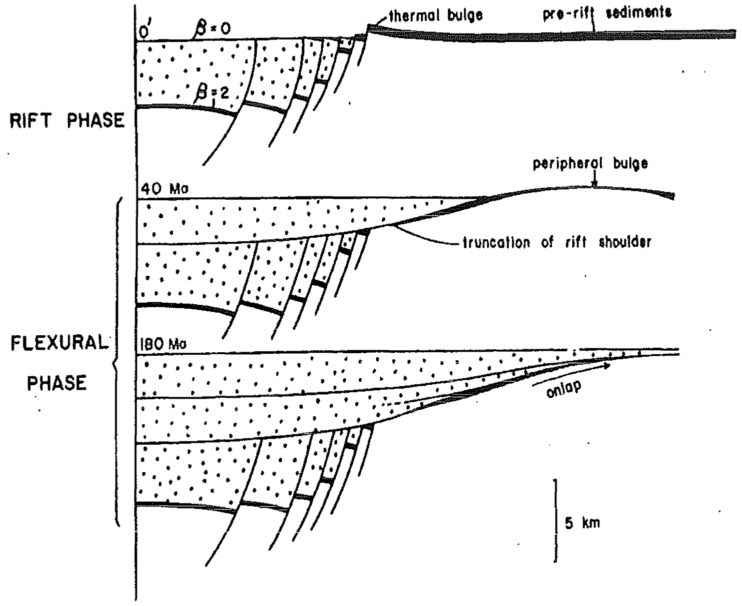
In rift basins, the controls on basin development are extremely complex and many considerations are needed when interpreting the mechanisms involved during basin evolution. Over the depositional history of a basin the relative influence of faulting, subsidence, climate and eustasy can differ, especially with the transition from the synrift to post-rift phases of basin development, where there is confusion over interpreting the transitional facies. It is generally accepted that syn-rift deposits are controlled by fault margins and show responses to fault movements, whereas post-rift deposits are typically controlled by subsidence due to thermal cooling after faulting has ceased (Einsele, 2000). This is usually seen as the overtopping of fault blocks by sedimentation and the extent of a broader basin is filled (Frostick and Steel, 1993). As a basin approaches the post-rift stage (i.e. is in the last stages of syn-rifting), there is significant confusion over controls on deposition. Are depositional facies still controlled by a syn-depositional framework or are they controlled by thermal subsidence (passive deposition), or both?

When sedimentation occurs in response to fault movements, and is essentially controlled by the uplifted flanks of the fault margins, the resulting basin fill is known as syn-rift facies (Leeder, 1995). During syn-rift deposition, sediment is typically transported basinward from the rift shoulders, or directly outward from perpendicular fault scarps. This usually occurs via alluvial fans and delta systems, although this may be modified by bedrock lithology, and/or the influence of climate (Leeder and Jackson, 1993; Leeder, 1995).

Syn-rift sediment packages typically onlap onto basement or older strata forming asymmetric wedge shaped packages thickening towards the master normal fault (Figure 5.2) (Miall, 1996). However, the detailed geometry depends on the degree of structural complexity, relative sea level change, and volcanism (Frostick and Steele, 1993). These can make lateral correlations problematic due to the often multidimensional nature of environmental responses to one or more allogenic factors.

The post-rift phase of basin development is attributed to thermal cooling of the lithosphere (Miall, 1990; Einsele, 2000). During the thermal cooling phase of basin development, depositional facies evolve in response to a decrease in active faulting and an increase in regional subsidence (Frostick and Steel, 1993). Fault blocks are laterally and vertically succeeded by sediments (Miall, 1990), in which they are successively overtopped and draped by sediment packages which may undergo fining upwards cycles (Frostick and Steel, 1993). Soft sediment deformation due to gravity induced sediment flows and listric growth faulting along with other slump features are characteristic of passive margin deposition (Frostick and Steele, 1993). Post-rift deposits are characterized by the seaward thickening of sediment (usually marine), which is often separated from syn-rift facies by an unconformity that indicates the 'break up' and beginning of continental drifting (Falvey, 1974; Frostick and Steele, 1993; Einsele, 2000). Post-rift deposits are seen to overtop syn-rift fault scarps, and are thus controlled by less localised mechanisms than local fault activation.

Thermal cooling is the primary model suggested for post-rift subsidence (Miall, 1990). McKenzie (1978) noted that during continental extension the crust is increasingly thinned and stretched. Upwelling of material from the athenosphere rises to compensate for the thinner crust, resulting in an increased geothermal gradient. When this crust is cooled back to the gradient that was in place prior to extension, the crust has an increased density, which causes subsidence (Miall, 1990). Combining these subsidence mechanisms with the influence of flexural loading (e.g. sediment weight), has given rise to the Texas Longhorn Model (Figure 5.2) which has been used to explain some intracratonic basins, failed rifts and rift to passive margin sequences (Miall, 1990).



The steer's head or Texas longhorn model of basin geometry. An initial rift phase is generated by rapid crustal stretching, resulting in listric normal faulting and ductile flow of the lower lithosphere, with Airy-type isostatic subsidence. The thermal anomaly generated during this phase causes an uplifted thermal bulge, which typically is eroded subaerially, forming an unconformity. The thermal anomaly then decays, resulting in relatively slower subsidence. The flexural strength of the lithosphere causes the sediment load to be spread over a wider area than during the first phase of basin subsidence, creating the horns of the model. (From Dewey, 1982. Reprinted by permission of the Geological Society, London.)

Figure 5.2: The Texas longhorn model (Miall, 1990).

Depending on the proximal setting of the basin, the evolution from syn to post-rift status may exhibit a variety of depositional facies. Miall (1990) summaries these as a three-part process (Figure 5.3):

Evolutionary Stage	Basin Development Stages	Structure/Stratigraphy	Sedimentary Environment
1	Syn-Rift	Rift basin has many active faults, with subsidence characterised by down-dropped half grabens and sag basins	These basins are filled with fluvial-lacustrine sediments, interbedded with volcanics
2	Transitional Syn to Post-Rift	Some active faulting, blanket-like deposits in basin. Drapes over horsts.	Marginal fluvial, lacustrine, fan delta. Sediments in the central basin may be either organic shales or evaporates. Or in the case of marine, carbonate platforms and basinal pelagic deposits. Some starved sequences may occur within deposits
3	Post Rift/ Thermal Subsidence	Few active faults, seaward thickening sediment wedges (clinoforms). Regional unconformities and onlap-offlap relationships.	Continental Coast with a clastic depositional system, or a Carbonate platform, or mixed clastic-carbonate.

Figure 5.3: Basin development stages, After Miall (1990).

5.2 BASIN DEVELOPMENT IN THE KAITANGATA COALFIELD

The Kaitangata Coalfield encompasses both syn and post-rift phases of basin development. The Henley Breccia and Lower Taratu Formation represent synrift deposition within the coalfield, with locally sourced facies controlled by the active Castle Hill fault scarp. The Middle Taratu Formation represents transitional syn-post rift basin development with influences from both local and regional basin controls on source and basin development. The Upper Taratu Formation characterises post-rift basin development with depositional sequences overtopping the Castle Hill fault margin and a broader basin filled. This phase of basin development is primarily due to regional controls on sedimentation and subsidence.

5.2.1 Henley Breccia

The coarse angular breccias of the Henley Breccia represent syn-rift facies in the Kaitangata Coalfield. However, dating the age of deposition of the Henley Breccia is problematic due to poor fossil preservation, although R.A. Couper gives a rudimentary age of the basal Henley Breccia as no older than Albian based on the presence of Angiosperm leaves in concretions (Harrington, 1958). The Henley Breccia is interpreted as syn-rift deposits due to the location, thickness and angularity of the facies. The Henley Breccia is composed of local fault scarp material, which can be traced to its source as it corresponds to textural zones of the Caples Group (Bishop and Turnbull, 1996). The thick brecciated nature of the Henley Breccia indicates it was deposited proximal to its source, the fault scarp on the rift shoulder.

The Taratu Formation encompasses both the syn-rift and post-rift phases of basin development, which change from the Lower, Middle and Upper Taratu members. The Lower Taratu Formation members are distinctly different from the Middle and Upper Taratu Members, both in composition, size and depositional setting. Lower Taratu Formation deposits are greywacke clast dominated with a minor schist and quartz component to conglomerates and coals are low in sulphur. In contrast, the Middle and Upper Taratu Members lithologies are strongly quartz dominated with high sulphur coals.

As the depositional style and facies architecture is intrinsically connected to autogenic and allogenic controls, understanding why there is a fundamental shift from greywacke to quartz-dominated lithologies, and a change from low to high sulphur coals is significant in interpreting the controls on basin development.

5.2.2 The Lower Taratu Members

Lower Taratu Formation conglomerates vary between local greywacke clast-supported, sub-angular, pebble to cobble conglomerates and matrix-supported, sub-angular pebbles, with a coarse sandy/muddy matrix. Clast supported conglomerates are interpreted as the result of paleochannels sourced from the Castle Hill Fault scarp onto a low relief alluvial fan. Matrix supported conglomerates have been interpreted as debris flows directly off the Castle Hill Fault scarp shoulders. Coarse sediment forms a well-defined clastic wedge due to the topographic relief provided by the downthrown side of the Castle Hill Fault. Peat bogs formed in swamp areas proximal to the Castle Hill Fault on a low-lying, humid climate alluvial fan. Coals from these deposits are low sulphur indicating they were terrestrial. Deposition of these coals was periodically interrupted by conglomerate truncation during times of tectonic activity or during flooding events. The Henley Breccia and Lower Taratu Formation correspond closely to Miall's (1990) evolutionary stage one of rift basin development (Figure 5.3), except that volcanic activity was not present in this basin during this stage. Primarily, what defines the Lower Taratu Formation Members as rift basin deposits is the presence of an active fault scarp controlling facies development and basin architecture. The development of a clastic wedge proximal to the fault scarp is a characteristic feature of rift basins, indicating asymmetry in depositional facies caused by movement on the fault. Tectonic activity is supported by the presence of unconformities created by conglomerates stepping out into peat bogs defining the stratal packages. Moreover, such erosional events are indicators of tectonic activity, although it is noted that flooding events may also be climate related.

5.2.3 The Middle Taratu Members

A change in depositional environment occurs between the Lower and Upper Taratu Members. This is seen as a change from greywacke dominated conglomerates to quartz dominated, although a greywacke component is still present proximal to the Castle Hill Fault (McClelland, 1984) and where facies pinch out on basement highs (Barry 1985).The quartz conglomerates are different in both clast size and structure from the greywacke conglomerates. The Middle Taratu conglomerates are finer, typically subangular, granules, with well-rounded anomalously large cobbles. There is also a considerable component of very angular, very coarse quartz sands to granules. Conglomerates are either interbedded with mudstones, siltstones and coals or massive with no obvious structure. Coals show a similar relationship with conglomerates to that observed in the Lower Taratu Members, with coal commonly truncated by conglomerates, or lateral coals splitting associated with interfingering conglomerates. In the upper Middle Members coals become more pod shaped constrained laterally by stable paleochannels, which can be seen to extend from the Castle Hill Fault. As these paleochannels differ in composition from the local basement it is interpreted that these paleochannels are extrabasinally sourced.

A change in coal chemistry is also notable in the Middle Taratu coal measures, with coals increasing in sulphur upward. By the time of the deposition of the Barclay Member coal horizons are concurrent with marine dinoflagellates and high sulphur, indicating a marine influence.

The depositional environment of the Middle Taratu Members resembles closely Miall's (1990) evolutionary stage two of basin development (Figure 5.3), where active faulting still occurs but sediments begin to drape over faults, in this case the extrabasinal paleochannels drape over the Castle Hill Fault. In the Kaitangata Basin this is reflected by a reduction in the local controls on sedimentation, as can be seen with the decrease in greywacke clasts from local basement source over time, replaced with extra-basinal, quartz dominated clastic material. However, the Castle Hill Fault scarp is still interpreted to be active due to the presence of local greywacke dominated facies occurring in drillholes proximal to the fault zone and is still present at the basins margins. This change in basinal evolution is also reflected in the depositional setting. As the distally sourced sediment component began to dominate the basin fill via paleochannels from the north and across the Castle Hill Fault scarp a more regionally influenced delta plain formed.

5.2.4 The Upper Taratu Members

The Upper Taratu Members have a similar description to the Middle Taratu Members, being composed of quartz rich conglomerates interbedded with sandstone, mudstones and coal, with one distinct difference. The depocenter of coal deposition, which was previously only on the downthrown side of the Castle Hill Fault, broadened to include the Benhar Sector. During the deposition of the lower Upper Taratu Members, lateral and vertical growth strata topped the Castle Hill Fault and deposition began in the Benhar Sector which was previously a paleohigh.

Upper Taratu Members show more segregation in lateral facies architecture than the Middle or Lower Members. The southern Benhar Sector is generally much finer grained than the northern Benhar Sector (Mc Clelland 1984). The southern Benhar Sector is composed primarily of interbedded mudstones, sandstones and coal with minor conglomerates. The Northern Benhar Sector has thick conglomerates interbedded with pebbly quartz sandstones, mudstones, and coals. In the Kaitangata Sector significant proportions of the Upper Taratu Members have been removed due to post-depositional erosion, and the facies geometry is considered generally much coarser except for the initial stages of deposition. During the early stages of the Castle Hill Fault being overtopped, minimal clastic input occurred. This can be seen where the Penman coal seam thickens considerably over the Castle Hill Fault but then thins to carbonaceous mudstones and interfingers with conglomerates to the north (Barry 1985). During Upper Taratu deposition the coals become sulphur rich, concurrent with marine dinoflagellates (Browne, 1986). The presence of glauconite is also noted interbedded with upper coals and carbonaceous mudstone indicating an intermittent marine influence on deposition (Raymond, 1985).

The depositional setting of the Upper Taratu Members is interpreted as a lower delta plain, with the southern Benhar Sector's fine grained facies relating to a low lying lake or back barrier estuary environment (Raymond 1985). The northern Benhar Sector is thought to be the limits of low lying swampy conditions and the interface between the peat bogs and well constrained paleochannels (Mc Clelland 1984; Raymond 1985).

This phase of basin development is related to Miall's (1990) third stage of rift basin evolution, the thermal subsidence stage (Figure 5.3). This is characterised by the termination of active faulting in which fault blocks are overtopped and a broader basin is occupied. At this time, the Kaitangata Coalfield ceased to be fault controlled and underwent thermal subsidence. This resulted in the widening of the basin margins to include the Benhar Sector as can be seen by the of thickening of the Penman coal horizon over the Castle Hill Fault. The long-lived presence of the paleochannels to the north of the Benhar Sector indicates the dominance of regionally controlled sedimentation during this time. The sporadic marine influence in the Upper Taratu Members increased over time. This is characteristic to the thermal subsidence stages of basin development in which transgressional marine facies increase dominance until a passive margin eventuates.

5.2.5 Wangaloa Formation

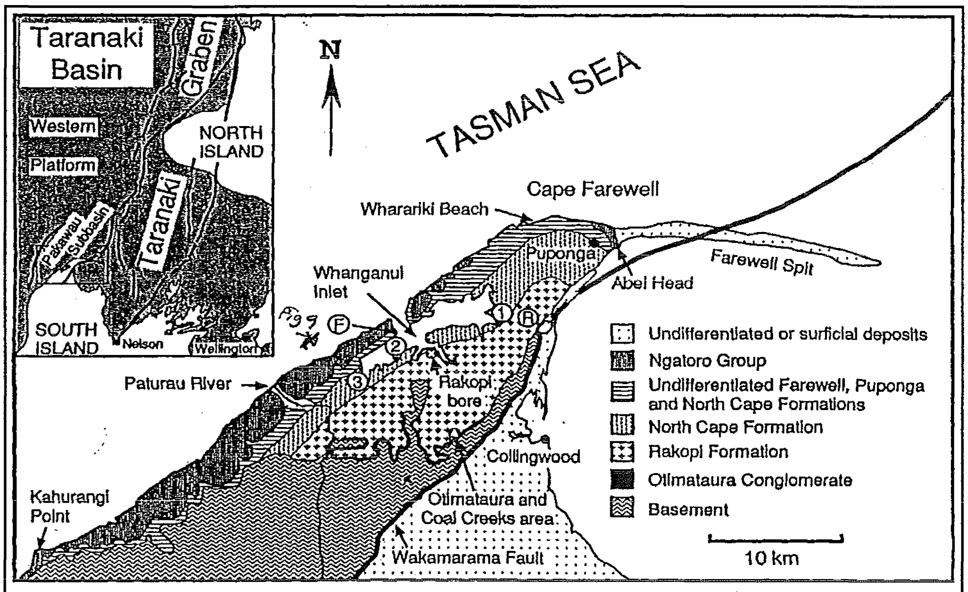
The contact with the overlying Wangaloa Formation, which represents the termination of terrestrial conditions, is recognised by a high gamma reflection that indicates the presence of glauconitic sandstone (Sherwood, *et al.* 1992).

Miall's (1990) third phase of rift basin evolution (Figure 6.3) notes that regional unconformities occur during this stage of basin development. McMillan and Nathan (1997) note the presence of unconformities in the Wangaloa Formation, Brighton Limestone and Abbotsfoot Formations south of Dunedin at the Cretaceous-Tertiary boundary. According to Raymond (1985) and Ward (2003 pers. comm.), the Cretaceous-Tertiary boundary occurs within the Upper Taratu coal measures making the Wangaloa Formation, Brighton Limestone and Abbotsfoot Formation laterally correlative.

5.3 THE CRETACEOUS PAKAWAU SUB-BASIN (TARANAKI BASIN)

A comparison of the Kaitangata Coalfield will be made with another coastal Cretaceous coalfield, the Pakawau sub-basin of the Taranaki Basin. The Taranaki Basin is a rift basin that initially formed during the separation of New Zealand from Gondwana in the Mid-Late Cretaceous during a time when the opening of the New Caledonian Basin occured (Thrasher, 1992). This created a series of half-graben sub-basins, such as the Pakawau sub-basin. Later during the Late Cretaceous, seafloor spreading in the Tasman Sea reactivated these older faults, causing pulses of fault activity, which in turn affected the stratigraphic architecture of these basins (Wizevitch, 1994).

The onshore exposure of strata relating to the reactivation of basin development is the Pakawau Group in Northwest Nelson. The Pakawau sub-basin is exposed along a 50 km belt of uplifted sediments exposed from Cape Farewell to Kahurangi Point and is constrained to the south by the north-east trending Wakamarama Fault (Figure 5.4). The Pakawau Group consists of the basal Otimataura Conglomerate that is overlain by the Rakopi Formation, North Cape Formation and Puponga Formation. This is succeeded by the Paleocene aged the Farewell Formation of the Kapuni Group.



General geologic map of study area. R and F refer to locations of Figures 5b and 9, respectively. Numbers refer to measured sections (1 = proximal to 3 = distal) in Figure 8. Inset shows location of study area. After Bishop (1971) and Thrasher (1992).

Figure 5.4: Location, structure and lateral distribution of the Pakawau Group onshore sediments (Wizevitch, 1994).

The Otimataura Conglomerate consists of thick successions of cobble sized conglomerates which are both clast and matrix supported, interbedded with lenticular cross-bedded sandstones (Wizevitch, 1994). The base of the formation primarily consists of polymictic conglomerates derived from local basement with maroon coloured interbedded breccias. The formation is primarily composed of micaceous schist and phyllite at the base, although there is an increasing quartz component towards the top of the unit. Conglomerates thin dramatically away from the Wakamarama Fault where it laterally interfingers with coal measures up to 50 cm thick. Clast supported conglomerates have weak horizontal stratification and poor clast imbrication whereas, matrix supported conglomerates have a brecciated component with no sorting structure.

The Otimataura Conglomerate is interpreted by Wizevitch (1994) to have been deposited as an alluvial fan on the downthrown side of the basin-bounding Wakamarama Fault. The clast supported conglomerates are considered to be part of bedload deposits of a braided river, with weak clast imbrication and horizontal stratification indicative of channel floor and longitudinal bars. Matrix supported conglomerates and fine breccias are considered to be deposits from debris flows. Wizevitch (1994) considers the dramatic lateral thinning of conglomerates to interbed with sandstones and coal as the outer limits of the alluvial fan.

The Rakopi Formation overlies the Otimataura Conglomerate and consists of fining upward cycles of sandstones, minor conglomerates and numerous coal seams. In drillhole nearly 80 coal seams less that 50 cm thick were encountered. These were interbedded with fine to coarse-grained tabular bodies, either fining or coarsening upwards and thicker channel-shaped bodies which consist of fining upwards coarse grained sequences (Wizevitch, 1994). These tabular bodies are cross-bedded, poorly sorted, coarse grained sandstones and pebbly conglomerates. Dinoflagellate cysts and glauconite pellets have been identified in the upper Rakopi Group.

The Rakopi Formation is interpreted as fining upwards channels through a fine-grained sequence deposited on a low gradient fluvial plain (Wizevitch, 1994). Channel structures indicate possible meandering rivers, which Wizevitch (1994) interprets to be high sinuosity channels on heavily vegetated alluvial plain. Where coals and sediments contain dinoflagellates, it was considered as a lower delta plain interdistributary bay or back-barrier lagoonal swamp.

The North Cape Formation is composed of interbedded conglomerate, sandstone and discontinuous mudstones but contains no coal bearing strata. Facies can be divided into three groups, proximal, medial and distal group. The proximal depositional facies consists of conglomerates and medium to coarse-grained sandstones with interbedded fine sandstones and mudstones. Coarse grained sandstones are planar, or have trough cross-bedding with thick mudstone drapes associated with both types of bedding. The clast composition is similar to that of the Otimataura Conglomerate Wizevitch (1994). Medial facies are fine and coarse-grained sandstones with cross or parallel laminated fine sandstones. Distal facies are predominantly mudstones, fine sandstones with carbonaceous and micaceous interbeds. Numerous bedding structures have been identified with rip-up clasts, ripple cross-laminated and cross-bedded bedded fine sandstone and mudstone. Bioturbation of sub-vertical tubes and the presence of dinoflagellates occur in areas with bi-directional ripples in fine sandstone (Wizevitch, *et al.* 1992).

The depositional environment of the North Cape Formation is interpreted to be a complicated combination of a low gradient fluvial delta with moderate to high energy for the proximal and medial facies. Distal facies containing with bi-directional flow, trace fossil and dinoflagellates are interpreted as an esturine environment (Wizevitch, *et al.* 1992; Wizevitch, 1994).

The upper part of the North Cape Formation and the Puponga Formation are laterally correlative. The Puponga Formation is dated as bridging the Cretaceous-Tertiary Boundary based on the diagnostic dinoflagellate species *M. Drugii*, which are identified in carbonaceous mudstones (Wizevitch, *et al.* 1992). Coals are up to several meters thick and are interbedded with sandstones and mudstones with rare conglomerates. The depositional environment is inferred to be a low gradient fluvial plain or marginal marine swamp environment (Wizevitch, *et al.* 1992).

The Pakawau Group is succeeded by the Early Paleocene aged Farewell Formation, which consists primarily of a thick succession of conglomerates, sandstones and mudstones with a rare coal component. The contact with the underlying Puponga Formation is erosional, with meter-sized clasts of coal and mudstone associated with cross-bedding. The Farewell Formation grades laterally from sandstones in the southwest, into conglomerates with paleocurrent measurements showing sediment transport away from the Wakamarama Fault (Titheridge, 1977). The depositional setting of the Farewell Formation is a braided river plain with lateral variation in clast size due to the differential uplift on Wakamarama Fault (Titheridge, 1977).

The strata of the Pakawau sub-basin is interpreted to be deposited primarily in a fluvial to deltaic regime, with the Otimataura Conglomerate and the Farewell Formation deposited in a high gradient fluvial setting whereas most of the Rakopi and Puponga Formations show traits of a low gradient fluvial setting (Wizevitch, 1994).

The depositional setting is further detailed by Wisevitch (1994) as a marginal marine for the upper Rakopi Formation and as a tidally influenced braid delta for the North Cape Formation, and paralic deposits for part of the Puponga Formation. This is interpreted as recording a Late Cretaceous marine trangression into the Pakawau sub-basin. The conglomeratic horizons are interpreted as recording pulses in tectonic activity, with climate and eustatic sea-level fluctuations as other influences (Figure 5.7) (Wizevitch, 1994).

The Pakawau sub-basin's sedimentary architecture indicates that depositional facies were controlled by movements on the Wakamarama fault. This can be seen as coarse grained sedimentary facies, shed from the fault margin either interfinger or blanket fine grained sequences throughout the history of the basin.

5.4 COMPARISON OF THE KAITANGATA COALFIELD TO THE PAKAWAU SUB-BASIN

The Taranaki Basin's Pakawau sub-basin shows many similarities with the Kaitangata Basin. Not only are they the same age, the tectonic development of the basins appears to have evolved in a similar fashion, with rift related facies dominating both basin histories.

Wizevitch (1994) has suggested that the Otimataura Conglomerate as a lateral correlative to the Hawks Crag Breccia (West Coast, South Island). Which in turn has been noted by Harrington (1958) to be a lateral correlative of the Henley Breccia. However, the correlation between the Otimataura Conglomerate and the Hawks Crag Breccia is not supported by tentative palynological dating which indicate that the Otimataura Conglomerate is Late Cretaceous in age, whereas the Hawks Crag Breccia is mid Cretaceous (Raine, 1984; Wizevitch, 1994). If palynological dating is correct, and the Otimataura Conglomerate is Late Cretaceous, it shows a better time correlation to the Lower Taratu Formation which is thought to be Late Cretaceous in age. The Otimataura Conglomerate in the Pakawau Basin also shows many similarities to the Lower Taratu Members; i.e. Both are composed of basement derived coarse clastics, which increase in quartz towards the top of the formation, and both show evidence for clastic wedge development proximal to fault boundaries in an alluvial fan setting.

The Rakopi and North Cape Formations show similarities with the Middle Taratu members. Deposits in both these basins have been described as interbedded conglomerates, coarse sandstones and mudstones with many coal seams with dinoflagellates (Barry, 1985; Raymond, 1985; Browne, 1986; Wizevitch, 1994). There is also a similarity in bedding structures, which is not surprising as these formations have both been characterised as vegetated lower delta plains with a marine influence due to the proximity of the coals to an interdistributary channel or back barrier bar.

The Puponga Formation of the Taranaki Basin is dated as straddling the Cretaceous-Tertiary boundary, which would make it the same age as Benhar Sector deposits in the Kaitangata Coalfield. Deposits in both these basins are considered marginal marine with the presence of dinoflagellates occurring with interbedded sandstones, mudstone and coals (Barry, 1985; Raymond, 1985; Browne, 1986; Wizevitch, 1994; Lindqvist ,1998). The Puponga Formation has rare conglomerates, as does the southern Benhar Sector; however, in the north Benhar Sector conglomerates are more prevalent and less similar to the Puponga Group deposits observed and are perhaps a better correlative to the North Cape Formation. Again, both depositional environments are characterised as marginal marine or a low gradient deltaic swamp (Raymond, 1985; Wizevitch, 1994).

The overlying deposits for both basins vary significantly. In the Kaitangata Coalfield the succeeding strata, the Wangaloa Formation, is primarily fine glauconitic sandstone interbedded with mudstones with trace fossils prevalent and is marine in origin. In the Pakawau sub-basin the overlying Farewell Formation (Kapuni Group) is comprised of conglomerate, sandstone and mudstone with rip-up clasts of coal and mudstones. This is interpreted as a braided river deposit. Therefore, as the Kaitangata Basin was becoming marine the Pakawau sub-basin was still borderline terrestrial and took longer to become a marine basin.

Although there are some differences to the successive deposits, the Taratu Formation and the Pakawau Group do show a very similar history. Furthermore, more similarities exist between the basins. The Wakamarama fault in the Pakawau sub-basin was a normal fault has a northeast-southwest trend (Wizevitch, 1994), similar to the Titri fault (in which the Castle Hill fault is probably a continuation of). Also, both these faults were active during the deposition, later becoming inactive. In addition, both these fault are attributed to basin development in different rift valley complexes.

5.5 OTHER CONTROLS ON BASIN DEPOSITION

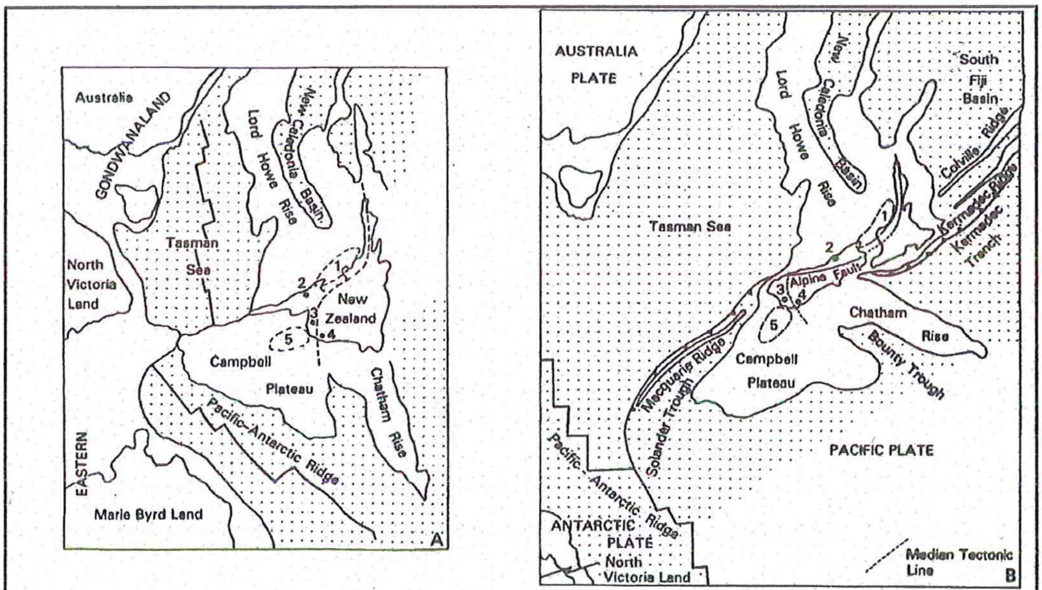
It is evident that the Kaitangata Coalfield was still tectonically active in the latest Cretaceous, when neighbouring east coast basins such as the Canterbury Basin were tectonically quiescent passive margins. During this time, the West Coast basins such as the Taranaki Basin were receiving influence from seafloor spreading in the Tasman Sea. Tectonic activity, as well as eustatic sea-level curves, are summarised in figure 5.7, which shows the Pakawau Members and timing of possible allogenic controls on deposition. It is hereby suggested that the Kaitangata Coalfield was also influenced from tectonic movements via transform faults from the Tasman Sea during rifting events. This is possible as the Wakamarama and Titri faults having a similar northeast orientation.

Depending on which tectonic reconstruction is used, the proximity of the Kaitangata Basin to other Cretaceous coal bearing basins is speculative. Sherwood *et al.* (1992) and King (2000) provide two different Late Cretaceous reconstructions in which the proximity of the Kaitangata Coalfield to the influence of tectonic activity would differ. Sherwood *et al.* (2000) place the Kaitangata Coalfield at considerable distance from the Taranaki and Greymouth Basins (Figure 5.5), whereas, King (2000) places the Kaitangata Basin closer and also indicates a notable portion of the New Zealand landmass was either low lying coastal or marine (Figure 5.6). King's reconstructions also highlight the proximity of the Kaitangata Coalfield to faults parallel to transforms on the Tasman Sea spreading ridge. The use of King's (2000) reconstruction also allows for better correlation of the Kaitangata and Taranaki basins, in which depositional sequences appear remarkably similar. It is evident from figure 5.7 that a variety of changes were occurring at this time, with sea-level fluctuations, climate change and the rates of seafloor spreading all strong contenders.

Significant changes were occurring in global climate approaching the Cretaceous– Tertiary boundary. New Zealand was at mid-high latitudes between 60-70° south which would be circum-polar, at latitudes (Nichols and Flemming, 1990). In a modern climatic regime, such latitudes would not be indusive of thick peat formation, as plant productivity and preservation potential is directly related to climate, and plant productivity would be very low (McCabe and Parrish, 1992). However, extensively thick coals are seen in Late Cretaceous basins in New Zealand at this time, including the Kaitangata, Ohai, Taranaki and Greymouth Coalfields.

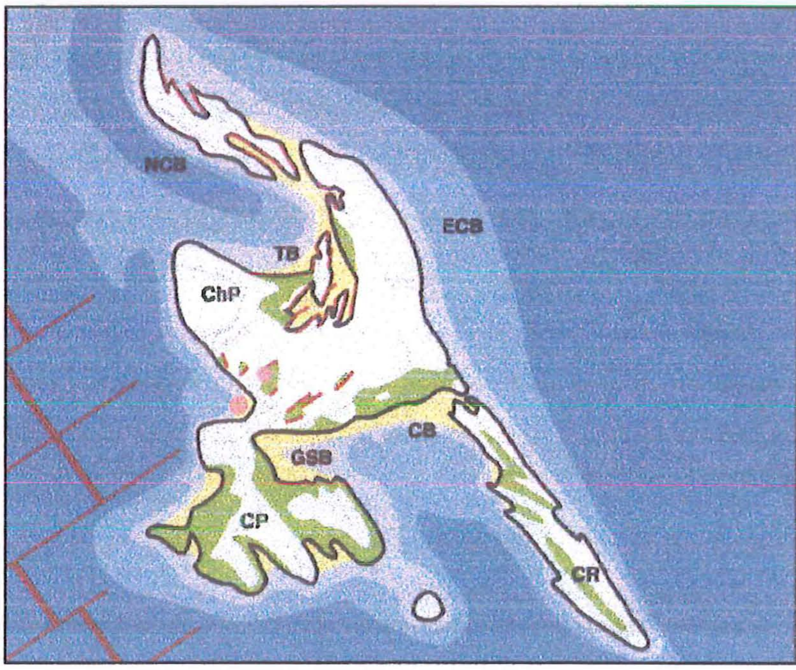
During most of the Cretaceous, it appears that conditions necessary for coal formation were not occurring in equatorial areas but were in higher temperate-cool latitudes. This has been attributed to a variety of factors such as continental configuration disrupting zonal climate circulation (Parrish *et al.* 1992; Crowley et. al 1989), the high seasonality of rainfall, or the lack of constrainment on Hadley cell circulation (Kemper 1987; Frakes and Francis 1988). However, for such extensive coals to be deposited (up to 45 meters thick in Kaitangata) in mid-high latitudes, climate must have been equitable, allowing for a high water table and high plant productivity for at least part of the year. Kennedy (1993) suggests a climate with an average temperature of 14° celsius, the equivalent of a cool-temperate climate based upon Late Cretaceous leaf assemblages from the Pakawau Group of northwest Nelson. Butler *et al.* (1988) suggest the Late Cretaceous climate was warm and dry until the Eocene, although New Zealand was more humid due to an oceanic influence.

High latitude coals similar to those seen in Kaitangata, have been described by Spicer *et al.* (1992) from the mid Cretaceous of northern Alaska. Spicer *et al.* (1992) notes that during the Cretaceous, coals were deposited at latitudes of 75° north or above. During summer months plant productivity of tree dominated mires was extremely high during a short growing season. This growing season ended abruptly, and within several weeks, the weather cooled significantly, with almost total darkness for the winter months. Subsequently, organic matter was preserved with little to no oxidation of peat material due to the rapid onset of partial or total freezing during the winter months. For plants to be able to survive with such extreme seasonal variability they would need to be able to survive near total darkness for the winter months and would be expected to be deciduous or colonising plant species that would recover quickly once warmer conditions prevailed. Ward (1993), using palynomorph data from Browne (1986), notes that Kaitangata flora was dominated by angiosperms and spores with only a minor gymnosperm component during the latest Cretaceous and Early Paleocene (Ward 1993).



A, New Zealand and the southwest Pacific in the Late Cretaceous showing the possible relative positions of major coal measure basins. 1, Taranaki basin; 2, Greymouth Coalfield; 3, Ohai Coalfield; 4, Kaitangata Coalfield; 5, Great South basin. B, The present plate-tectonic setting of New Zealand. Simplified after Kamp (1986). The Median Tectonic Line is an accretionary feature of Permian age, showing offset of 500 km by the Alpine fault in Figure 1B.

Figure 5.5: Late Cretaceous reconstruction of the New Zealand continent. (Sherwood, *et al.* 1994).



Latest Cretaceous c.65Ma

New Zealand continent drifting from Gondwana. Rift basins in central west, possibly part of a transform system linked to sea-floor spreading. Volcanism in Westland and probable high heat flow locally. Deposition of coal measure source rocks (green) and shoreline sandstones (yellow). See present day map for legend and caption for abbreviation definitions.

NCB=New Caladonia Basin, ECB= East Coast Basin, TB=Taranaki Basin, ChP=Challenger Plateau, CB=Canterbury Basin, CR=Chatham Rise, GBS=Great South Basin, CP=Campbell Plateau. Pink Circles=Active Volcanism

Figure 5.6: Latest Cretaceous reconstruction of the New Zealand continent (King, 2000).

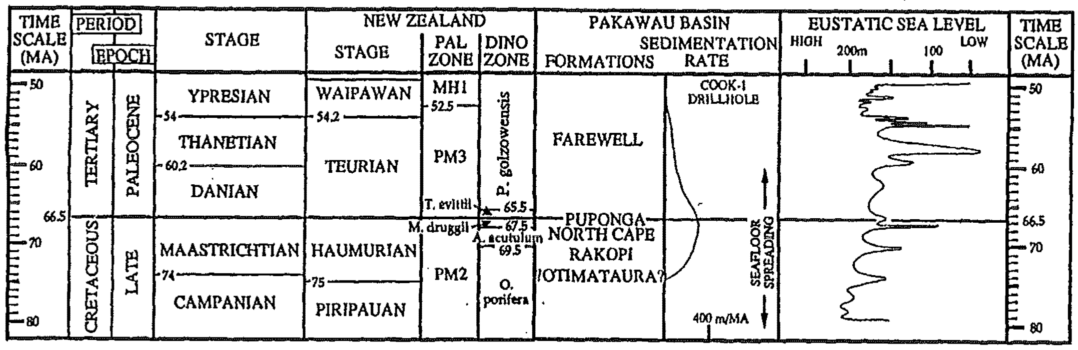


Chart showing time, New Zealand palynology (Raine, 1984) and dinoflagellate (Wilson, 1984; Pocknall et al., 1989) zones, sedimentation curve (Nathan et al., 1986), dates of sea floor spreading in the Tasman Sea (Weissel and Hayes, 1977) and eustatic sea level curve (Haq et al., 1987).

Figure 5.7: Relationship between Pakawau Formation Members biostratigraphic indicators, sea-floor spreading and eustatic sea-level curves (Wizevitch, 1994).

5.6 SUMMARY

The mid-Late Cretaceous-Early Paleocene of New Zealand was a time of considerable tectonic change, which had a significant influence of the stratigraphic development of New Zealand Late Cretaceous deposits.

Normal faults were active in the Kaitangata Coalfield in the Late Cretaceous, with the Castle Hill Fault scarp was still active until Penman deposition. Thus, the Kaitangata basin must be considered a rift basin at that time. Active fault blocks were then overtopped and the primary control on deposition became regional thermal subsidence. The Kaitangata Coalfield has many similarities to other New Zealand coal bearing basins, in particular the Taranaki Basin. A comparison of stratigraphy suggests a similar depositional history of fault controlled rift basin deposits. However, other allogenic controls such as climate and eustacy must be considered as influences on basin development.

CHAPTER SIX

CONCLUSIONS

6.1 SYNTHESIS OF ANALYSES

The main aim of this thesis was to investigate the controls on coal maturation (rank) in the Kaitangata Coalfield, South Otago, New Zealand. This was achieved by assessing controls on coal maturation and whether coal maturation is related to 'normal' basin processes, such as subsidence and burial, or if it has been modified to some degree by fault related processes and/or volcanic intrusions. To achieve this main objective, the study was designed to address four main goals. These were:

1) To create a stratigraphic framework to assess lateral continuity of seams,
2) assess vertical and lateral coal rank trends in the Kaitangata Coalfield,
3) provide an overview of the thermal and depositional evolution of the coalfield,
4) and delineate a basin history for the Kaitangata Coalfield.

The first goal, creating a stratigraphic framework for continuity of coal seams, was investigated in Chapter Three. Before assessing the coal rank, the vertical and lateral continuity of coal horizons were assessed so that an understanding of basinal history could be attained. This was important for several reasons. Firstly, so that the rank studies could be applied in context to the distribution of coals and sedimentary facies. Secondly, stratigraphic facies architecture is fundamentally connected to basin evolution, and this was required in order to achieve all of the other goals in this study. The basin architecture was assessed by constructing basin specific lithological coding allowing for a stratigraphic framework to be applied using cross-sections and coal thickness isopach maps. Lithostratigraphic analysis in this study identified three phases of basin development each associated with the deposition of a group of Members.

The facies architecture and depositional environment associated with the Lower Taratu Members indicated that low sulphur coals were commonly interbedded with greywacke conglomerates, sandstone and mudstone in a clastic wedge of sediment on the down thrown side of the Castle Hill Fault. Cross-sections and coal thickness isopach maps showed that vertical and lateral continuity of coals were primarily controlled by the Castle Hill Fault. The Lower Taratu Formation was sourced from local fault alluvium and paleochannels that truncated the fault scarp. Analysis of stratigraphy resulted in the conclusion that the depositional environment of the Lower Taratu Formation was an alluvial fan.

The Middle Taratu Formation Members are distinguished from the Lower Taratu Formation by the lithological change from greywacke to quartz dominated conglomerates, accompanied by an increase in sulphur content in coals. Similar to the Lower Taratu Formation, peat distribution and burial process in the Kaitangata Sector controlled by subsidence on the Castle Hill Fault, although, during early Middle Taratu times a significant extrabasinal quartz component was introduced to the basin via paleochannels across the Castle Hill Fault scarp as well as from the northern parts of the coalfield. The quartz component is finer in the middle Members than in the underlying Lower Taratu conglomerates and is interbedded with sandstones, mudstones and coals. The distribution of coals indicated that peat bog distribution was controlled by the presence of stable paleochannels. Deposition in the Barclay and Washpool coal horizons resulted in high sulphur as well as the presence of dinoflagellates which indicated that a marine influence was contemporaneous with coal deposition. This along with other indicators such as lateral facies changes helped characterise the depositional environment of the Middle Members as a lower delta plain.

The Upper Taratu Members are defined by the overtopping of the Castle Hill Fault and the initiation of deposition on the Benhar Sector, which was a paleohigh during the deposition of the Lower and Middle Taratu Members. Composition of lithofacies is similar to the Middle Taratu Formation, although laterally facies are fining towards the Southern Benhar Sector. Towards the top of the Upper Taratu Members coal horizons are interbedded with glauconitic sandstones and dinoflagellates indicating a marine influence. A depositional environment for the Upper Taratu Members is characterised as a lower delta plain.

From stratigraphic analyses completed in this thesis, the Capstick Member and Penman Members are reassigned from Harrington's (1958) classification of them as Middle Taratu Members. They are reclassified as Lower and Upper Members respectively. The Capstick Member is reassigned for two reasons. Firstly, interbedded greywacke conglomerates are diagnostic of the Lower Taratu Formation Members, whereas Middle Members are almost entirely quartz conglomerates. The Capstick Member is interbedded with greywacke conglomerates, hence it's reclassification. Secondly, rank studies further support the reassignment of the Capstick Member, as it shows a similar rank to that of the Jordan coal horizon, which Harrington (1958) classified as a Lower Taratu Member.

The Penman Member is the first coal horizon to be deposited in the Benhar Sector, which during Lower and Middle Taratu times was a paleohigh. This represents a new phase in basin development, thus the Penman Member should be attributed to this stage in the basin's history rather than the previous phase of basin development.

The second objective of this thesis was to assess vertical and lateral rank trends using Vitrinite Reflectance (VR), calorific value (CV) and volatile matter (VM). The results are given in Chapter Four.

Rank trends differed between the two sectors of the coalfield. The Kaitangata Sector overall showed a higher rank with depth, whereas, the Benhar Sector showed a marginal increase in rank with depth. Lateral rank trends showed the most variation in the Benhar Sector with rank increasing when approaching the Castle Hill Fault. The Kaitangata Sector had large variations in rank but a systematic increase could not be detected, except for in the Barclay coal horizon.

Burial depth appears to be the most influential factor on coal rank with the most deeply buried Lower Taratu Members showing the higher ranks compared to the less buried Middle and Upper Taratu Members. However, the rank attained by the most deeply buried coals indicates that the maximum geothermal gradient experienced by coals would not have exceeded 80°C over the ~65 million years of burial.

The influence of the Dunedin Volcanics igneous intrusions is poorly understood, primarily because of a lack of data density. Although, local increases in coal rank are depicted in the Barclay coal horizon showing higher ranks occurring in coals surrounding intrusive bodies. However, due to the lack of data such influences cannot be definitively characterised.

The final aim of this thesis was to detail the basin history of the Kaitangata Coalfield, which was accomplished in Chapter Five. This was achieved by placing the Kaitangata Coalfield's development in context with the tectonic development of the New Zealand region. This concluded with a comparison of the Kaitangata Coalfield to the Pakawau Sub-Basin of the Taranaki Basin in order to assess the controls on basin development.

The following basin history for the Taratu Formation was concluded. The Kaitangata Coalfield began as a syn-rift basin during the deposition of the basal Henley Breccia and Lower Taratu Formation. This can be classified as syn-rift as the Castle Hill Fault primarily controlled facies distribution and basin architecture. When the Middle Taratu Formation was deposited the influence of faulting was reduced, this is thought to be a transitional syn- to post-rift stage. When the Castle Hill Fault was overtopped and a broader extent of the basin was filled during Upper Taratu times, the associated depositional facies helped characterise the Kaitangata coalfield as a post-rift basin during that time. Thus, in contradiction to previous studies (e.g. Diesel, 1994), the Kaitangata Coalfield must be considered a rift basin until the active fault blocks were overtopped and the primary control on deposition became regionally controlled thermal subsidence.

The Kaitangata Coalfield has many similarities to other Late Cretaceous-Early Paleocene New Zealand coal bearing basins, e.g. the Taranaki Basin. A comparison of stratigraphy suggests a similar depositional history with fault controlled facies distribution. It is therefore suggested that tectonic influence from the Tasman Sea rifting events may have had an effect on these basins. However, other allogenic controls such as climate and eustacy must be considered as other potential influences on basin development.

6.2 FUTURE RESEARCH

There is plenty of scope for future research in the Kaitangata Coalfield. To date, it an under explored area, with diverse opportunities for future work. This thesis would have been greatly aided by better age constraint and climatic indicators and hereby suggests some areas for future research.

The characterisation of high latitude, humid climate, seasonally controlled, thick Cretaceous coals made by Spicer *et al.* (1992) to describe Cretaceous coals in Alaska, relied on the identification of growth rings in preserved branches and trunks. A similar study could be completed in the Kaitangata Coalfield, this would greatly aid the paleoclimatic understanding of the Late Cretaceous in New Zealand.

A second area for potential research would be providing age constraint on the coalfield. This could be achieved by either pollen studies or the identification of dinoflagellates species. Browne (1986) provided some preliminary age constraint and paleoenvironmental indicators using dinoflagellates, although, this was only done as part of a wider palynological study. Thus, a detailed account of dinoflagellates has not been assessed. A comparative study using Kaitangata dinoflagellates with diagnostic Cretaceous-Tertiary dinoflagellates in other New Zealand basins would hopefully greatly aid age constraints on the Kaitangata Coalfield.

6.3 SUMMARY

In conclusion, each group of the Taratu Formation Members is summarised according to their following attributes:

- **Lower Taratu Members**
  Low sulphur, highest rank coals deposited contemporaneously with greywacke rich conglomerates in an alluvial fan setting during syn-rift basin development.

- **Middle Taratu Members**

  High sulphur, coals of intermediate ranked coals (with localised higher rank areas), deposited with quartz rich conglomerates with limited influence of the Castle Hill Fault. Coals were deposited in a lower deltaic setting under transitional syn- to post-rift basin development.

- **Upper Taratu Members**

  Moderate to high sulphur coals, lowest ranked Taratu Formation coals (which increase in rank towards the Castle Hill Fault), Member characterised by overtopping of the Castle Hill Fault. Coals deposited with quartz rich conglomerates in a lower deltaic setting during post-rift basin development.

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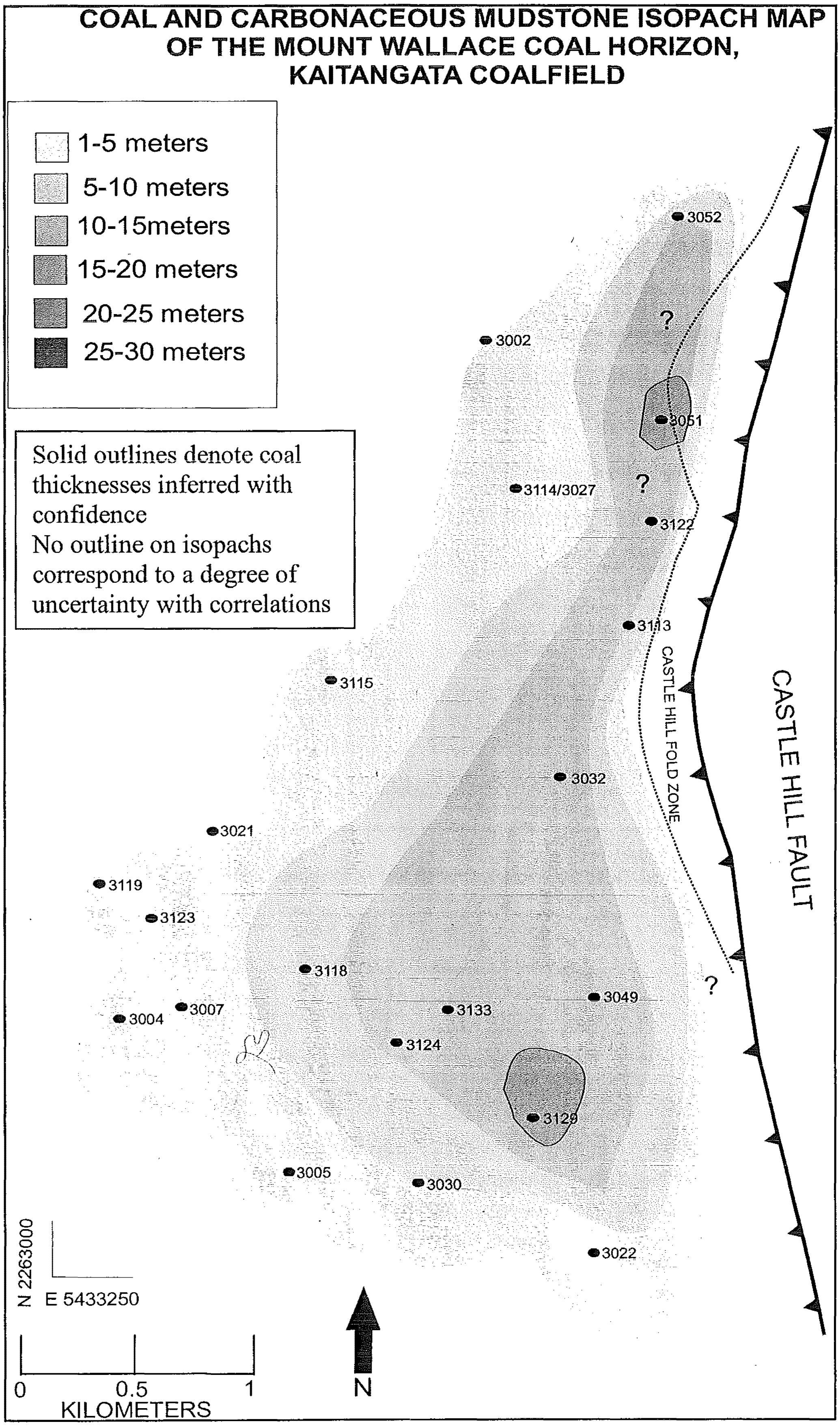
APPENDIX A

CROSS-SECTIONS

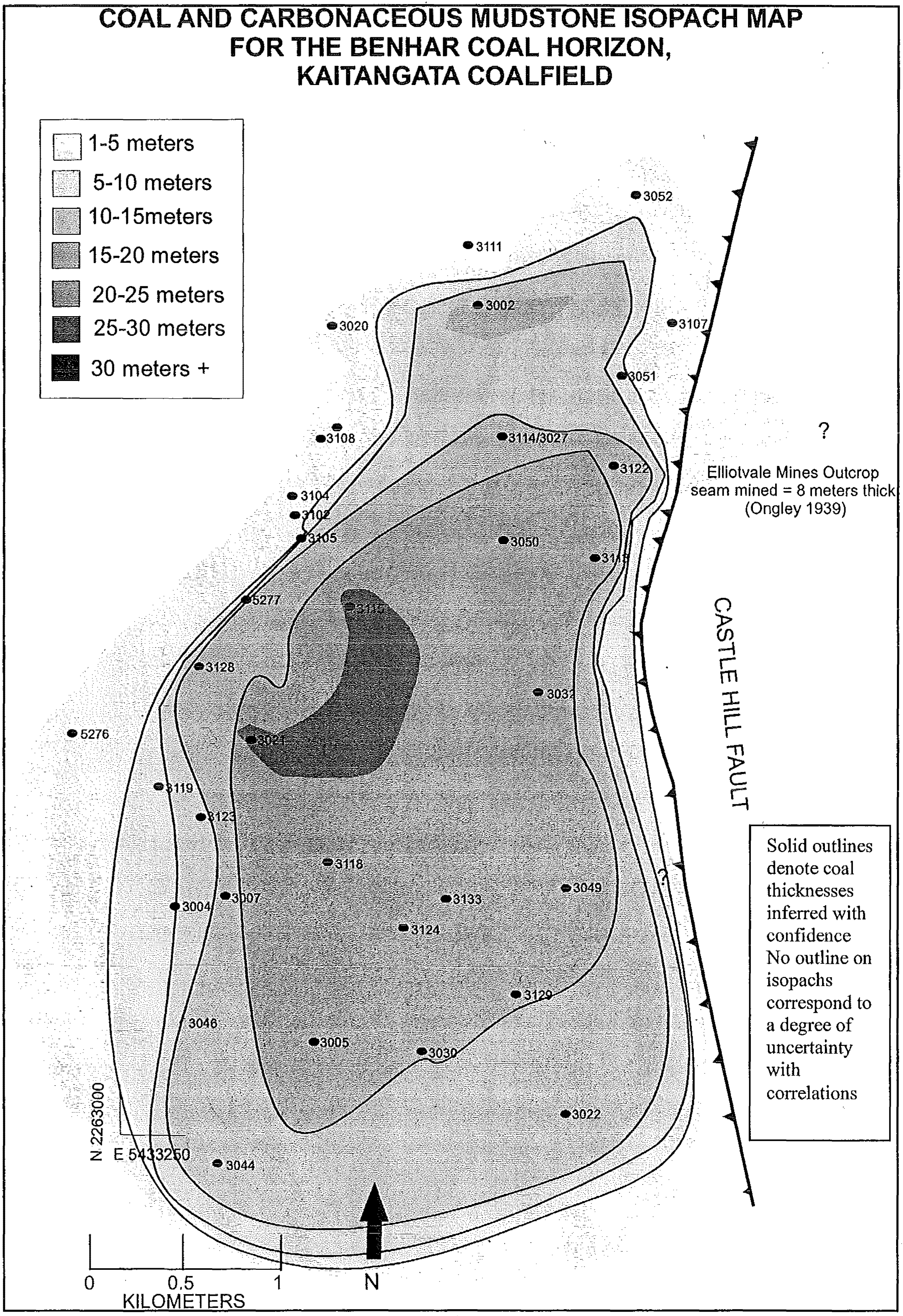
- Refer to cross-sections A-F in the map pocket at the back of the thesis.

APPENDIX B

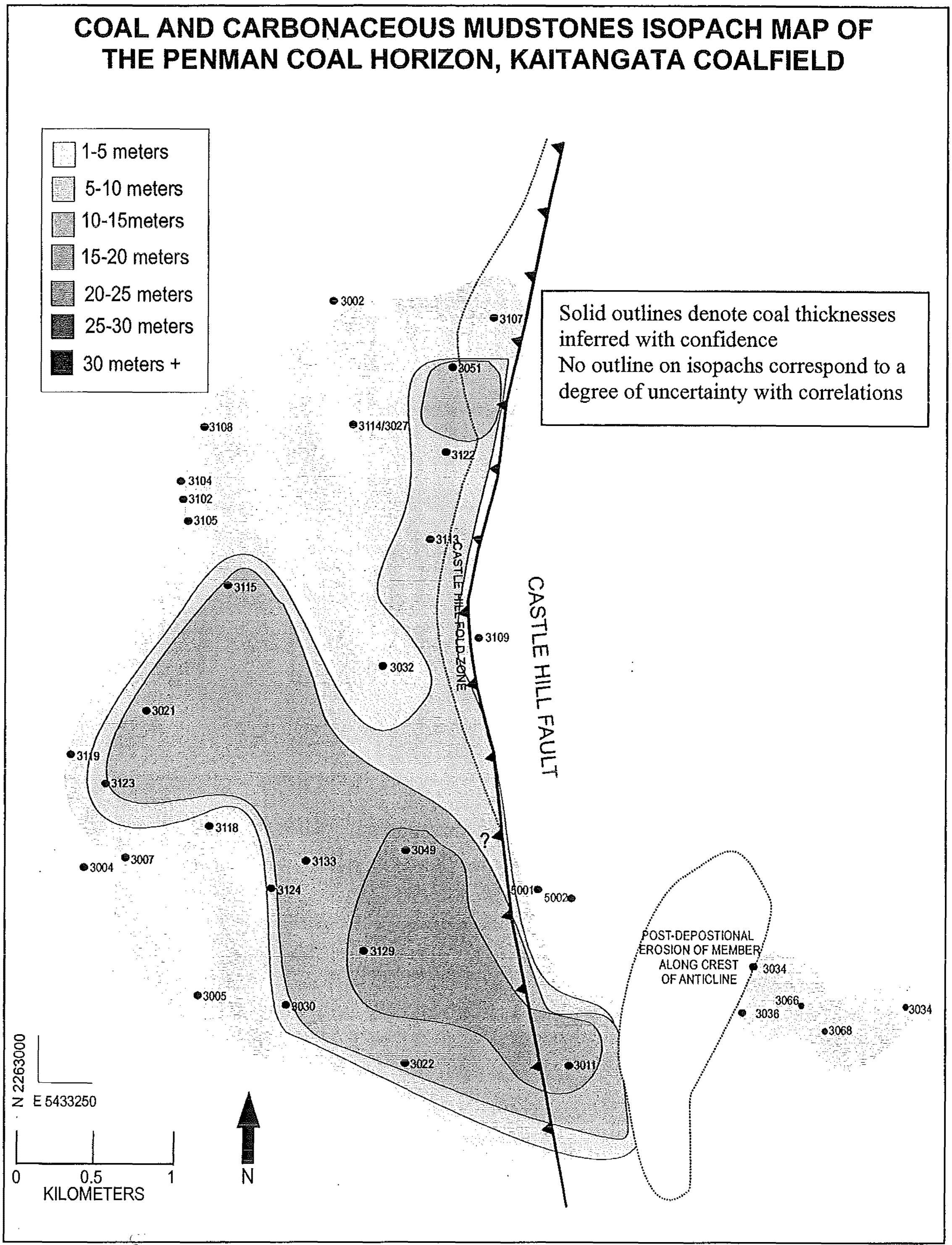
COAL ISOPACH MAPS



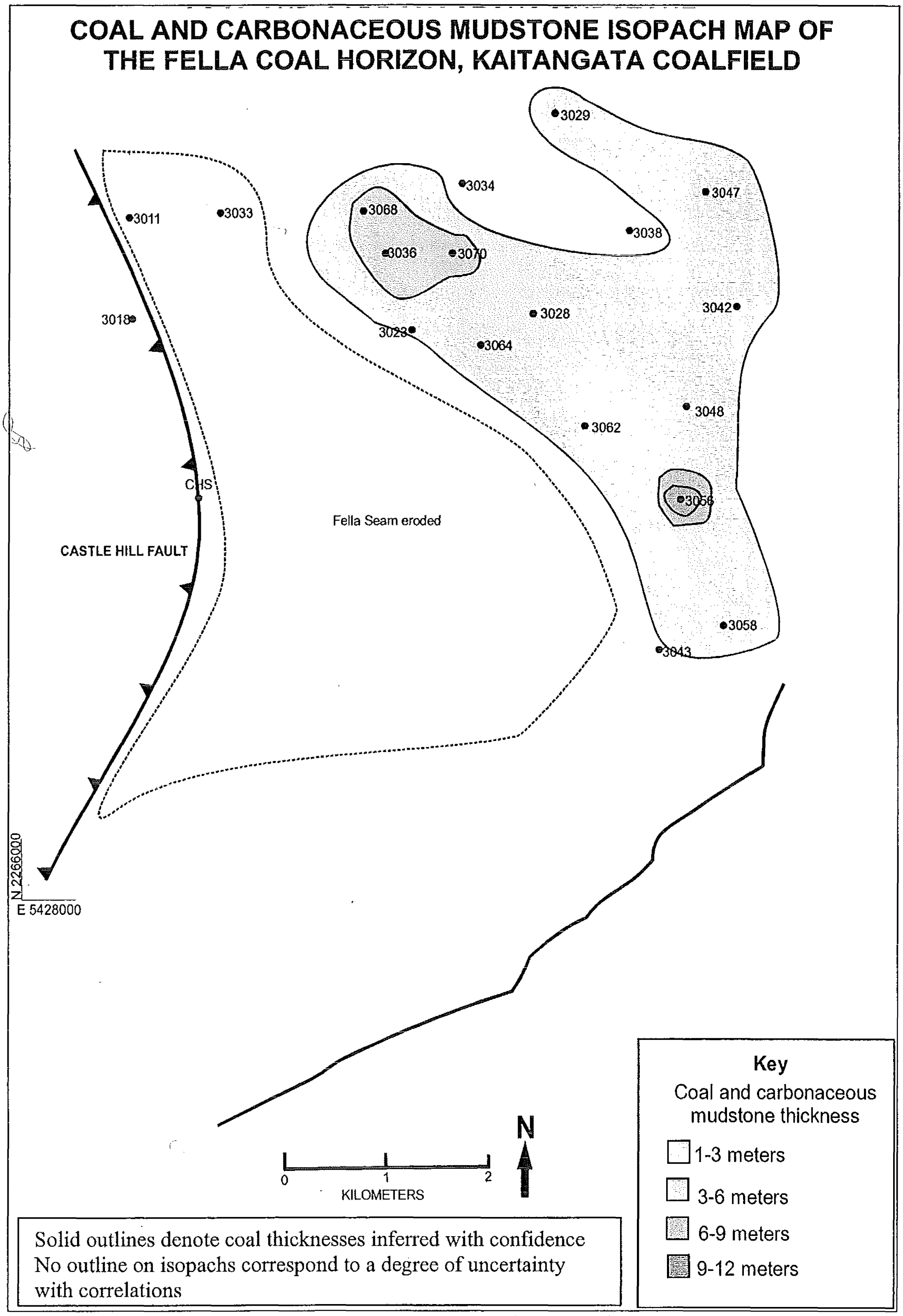
Appendix B1: Coal and carbonaceous mudstone isopach distribution for the Mount Wallace coal horizon.



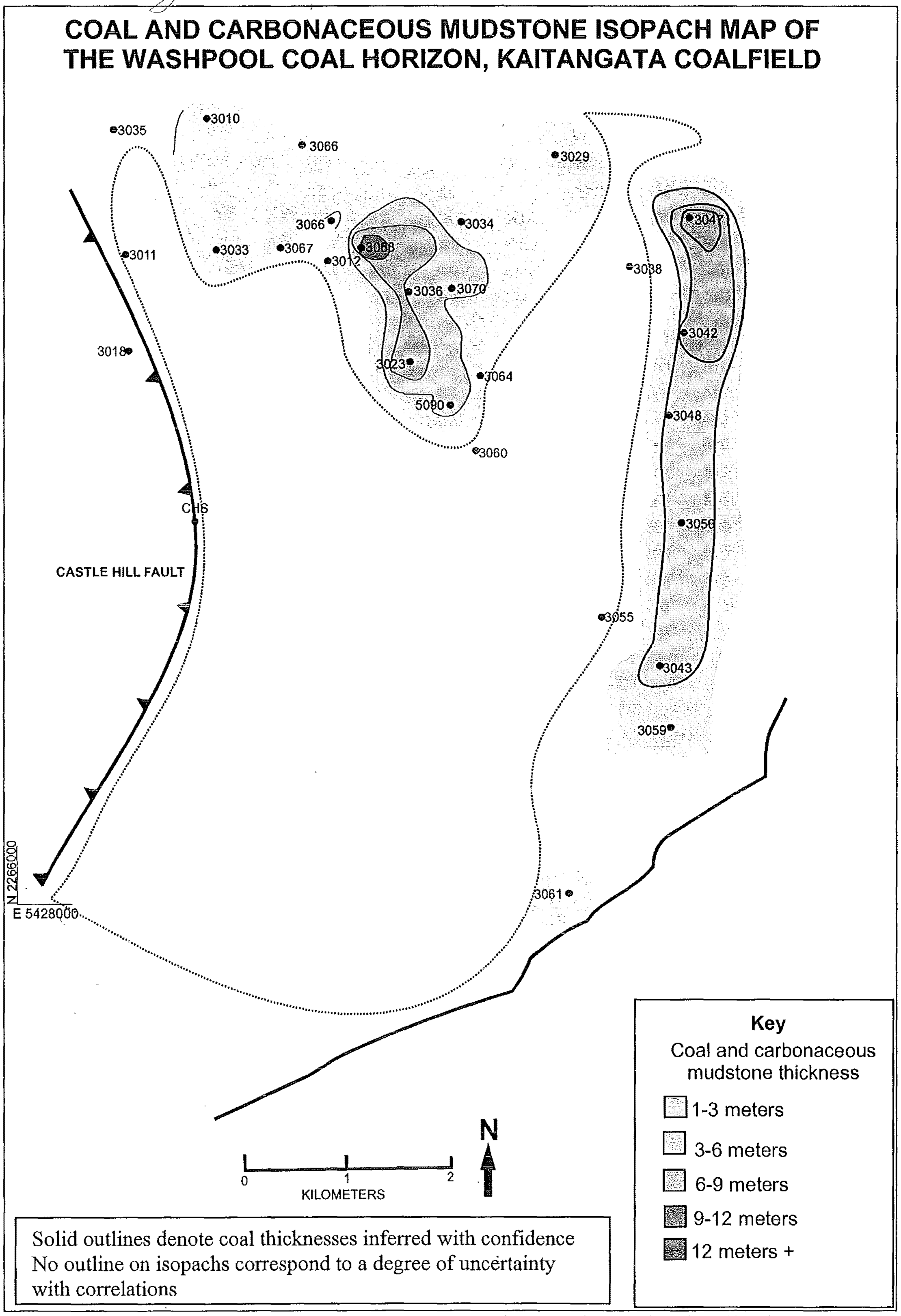
Appendix B2: Coal and carbonaceous mudstone isopach distribution for the Benhar coal horizon.



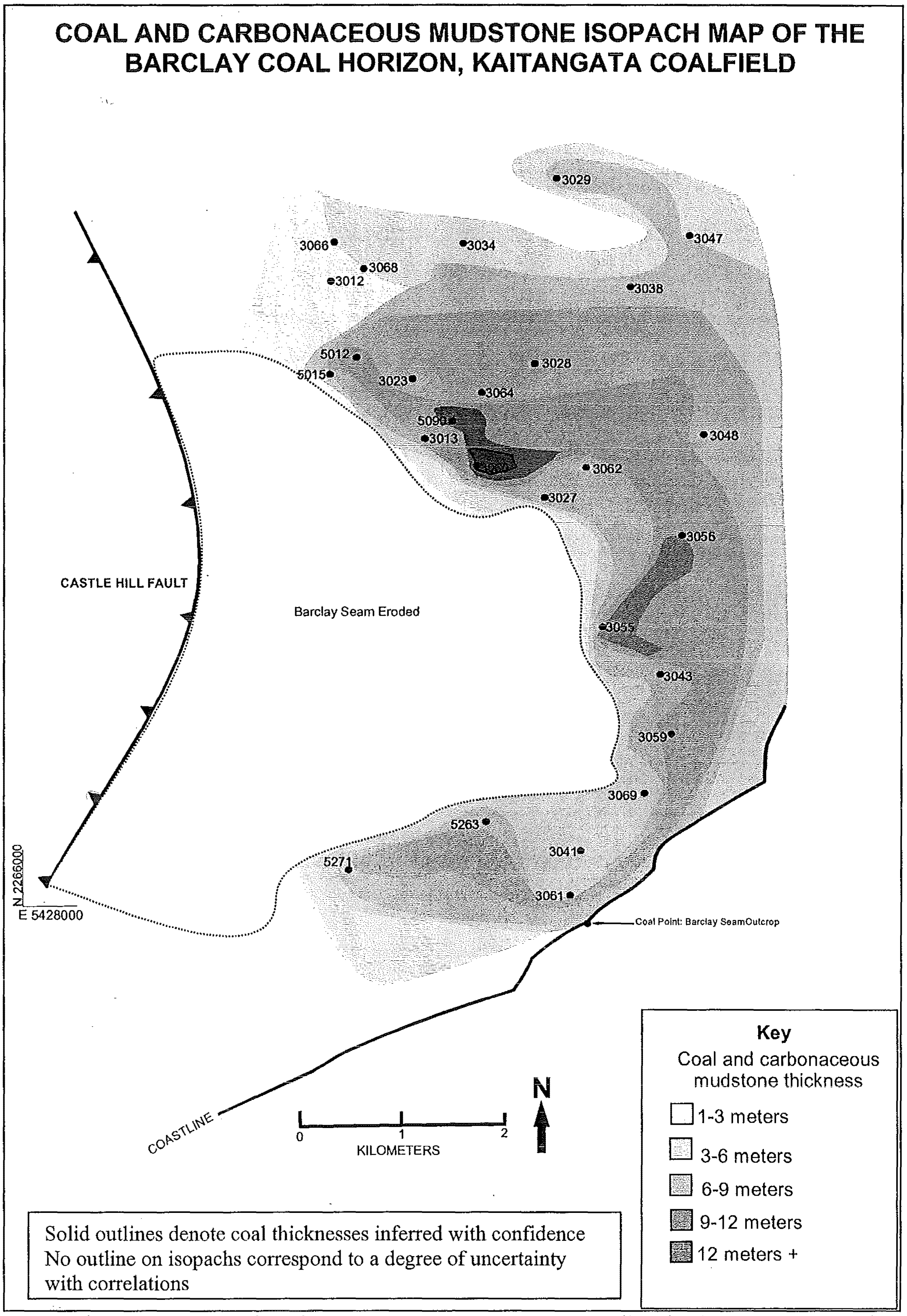
Appendix B3: Coal and carbonaceous mudstone isopach distribution for the Benhar coal horizon.



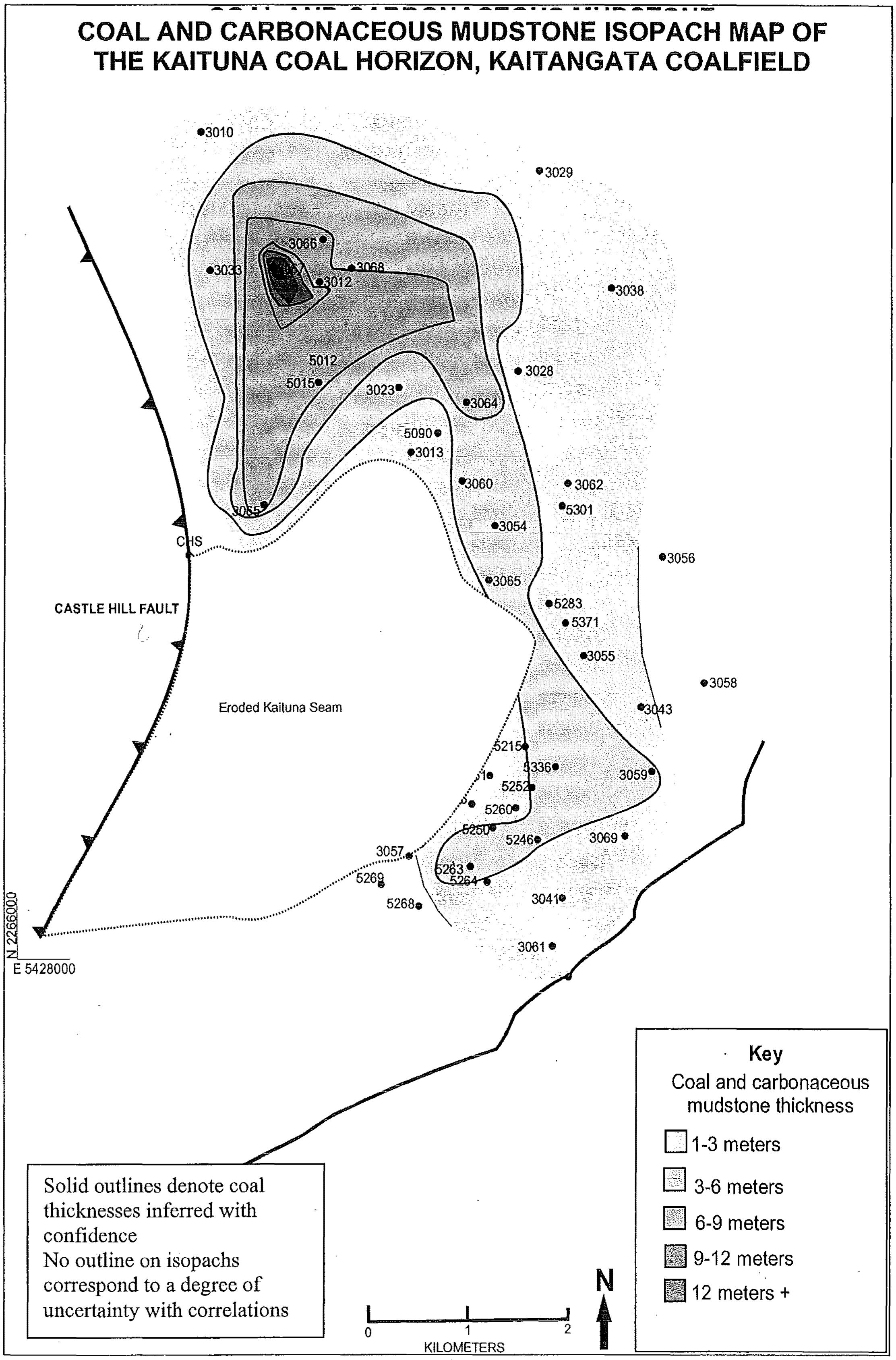
Appendix B4: Coal and carbonaceous mudstone isopach distribution for the Fella coal horizon.



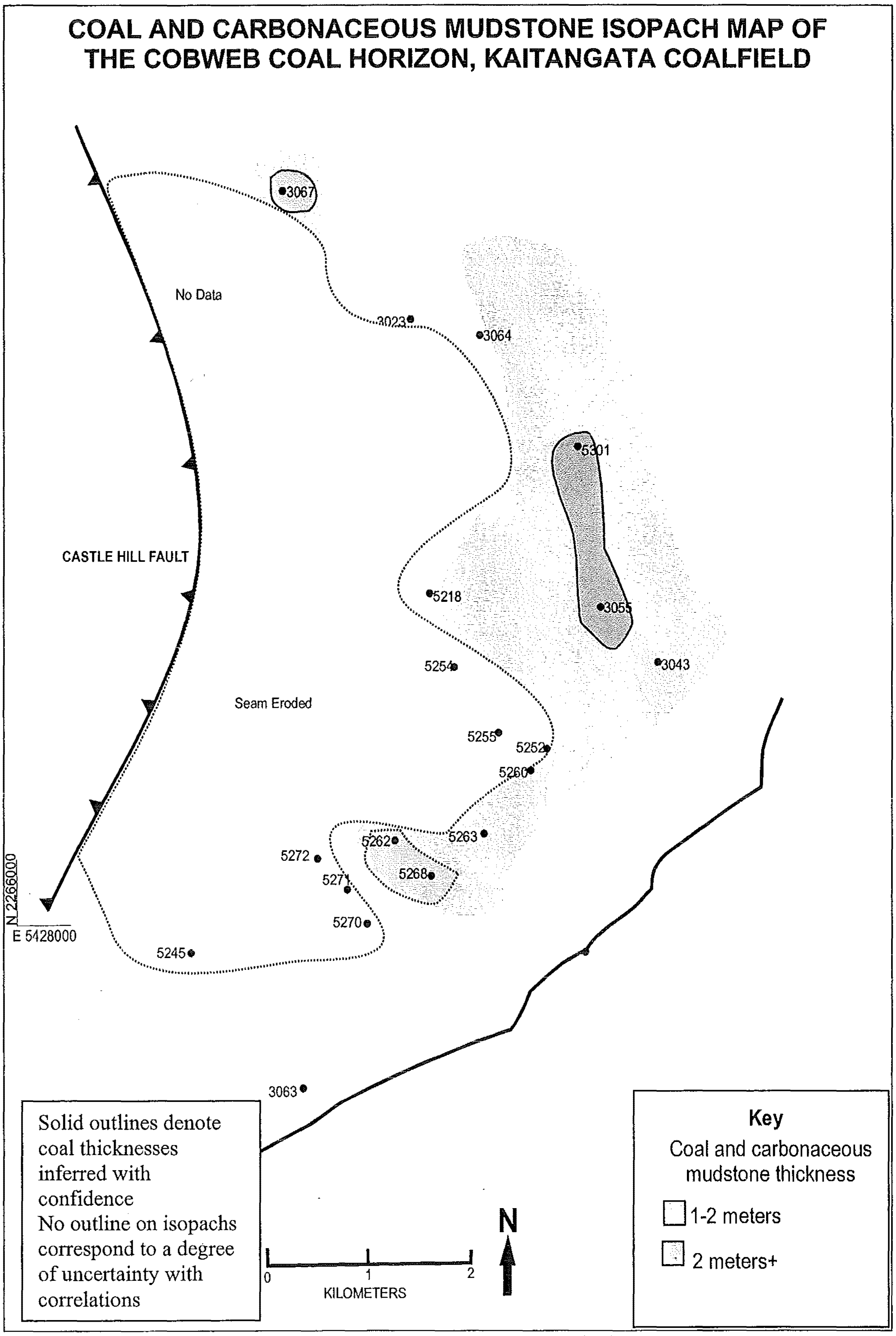
Appendix B5: Coal and carbonaceous mudstone isopach distribution for the Washpool coal horizon.



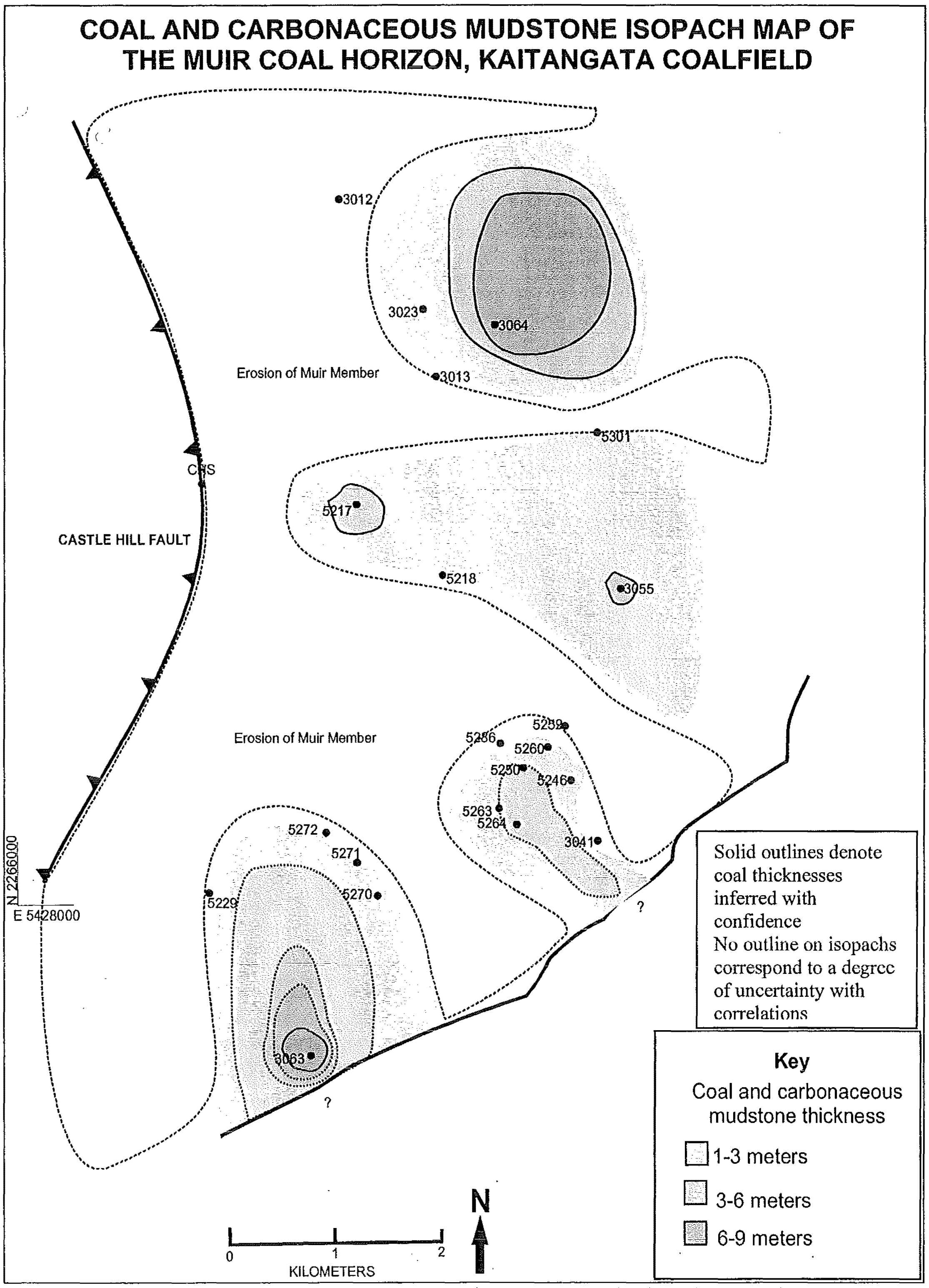
Appendix B6: Coal and carbonaceous mudstone isopach distribution for the Barclay coal horizon.



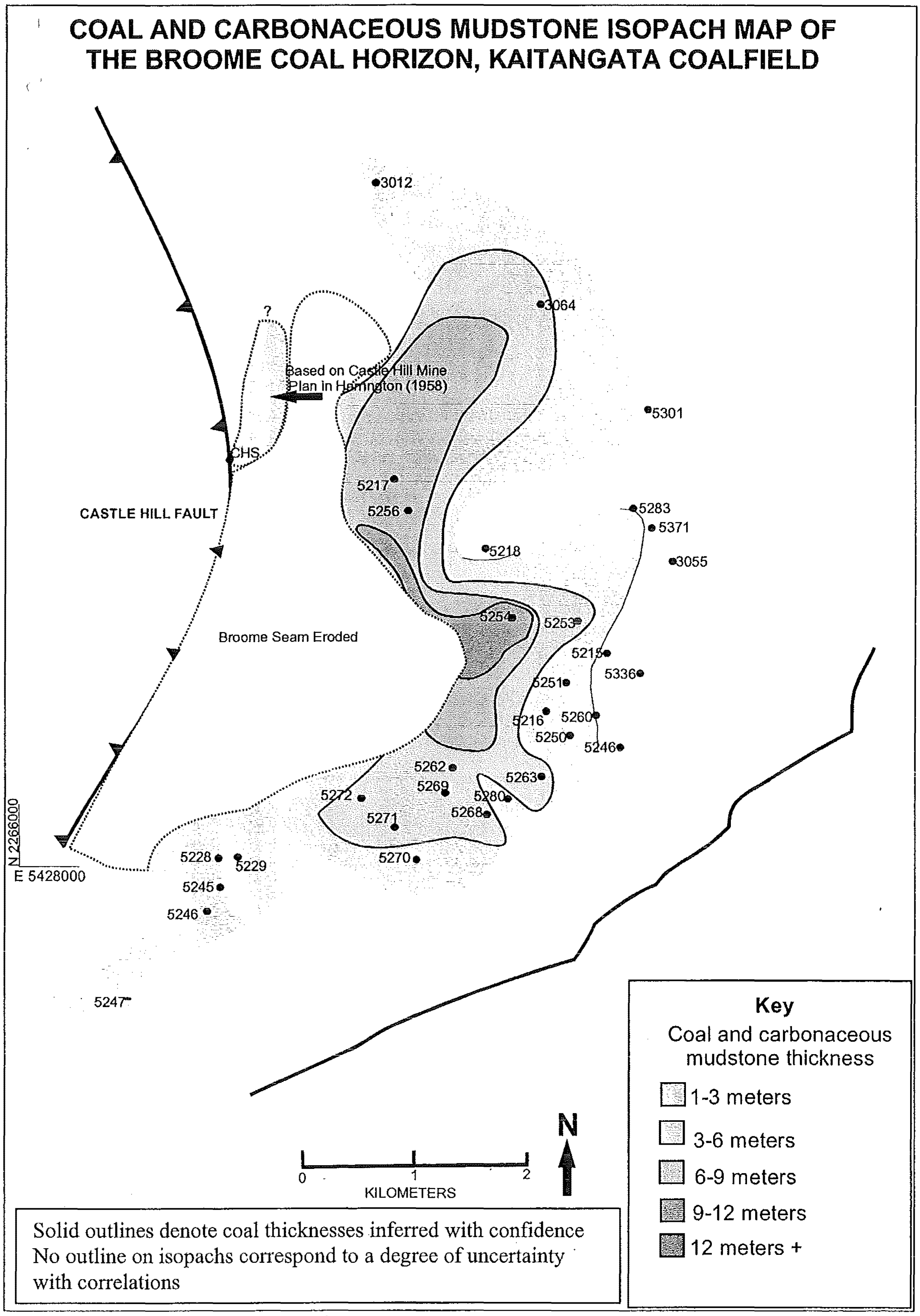
Appendix B7: Coal and carbonaceous mudstone isopach distribution for the Kaituna coal horizon.



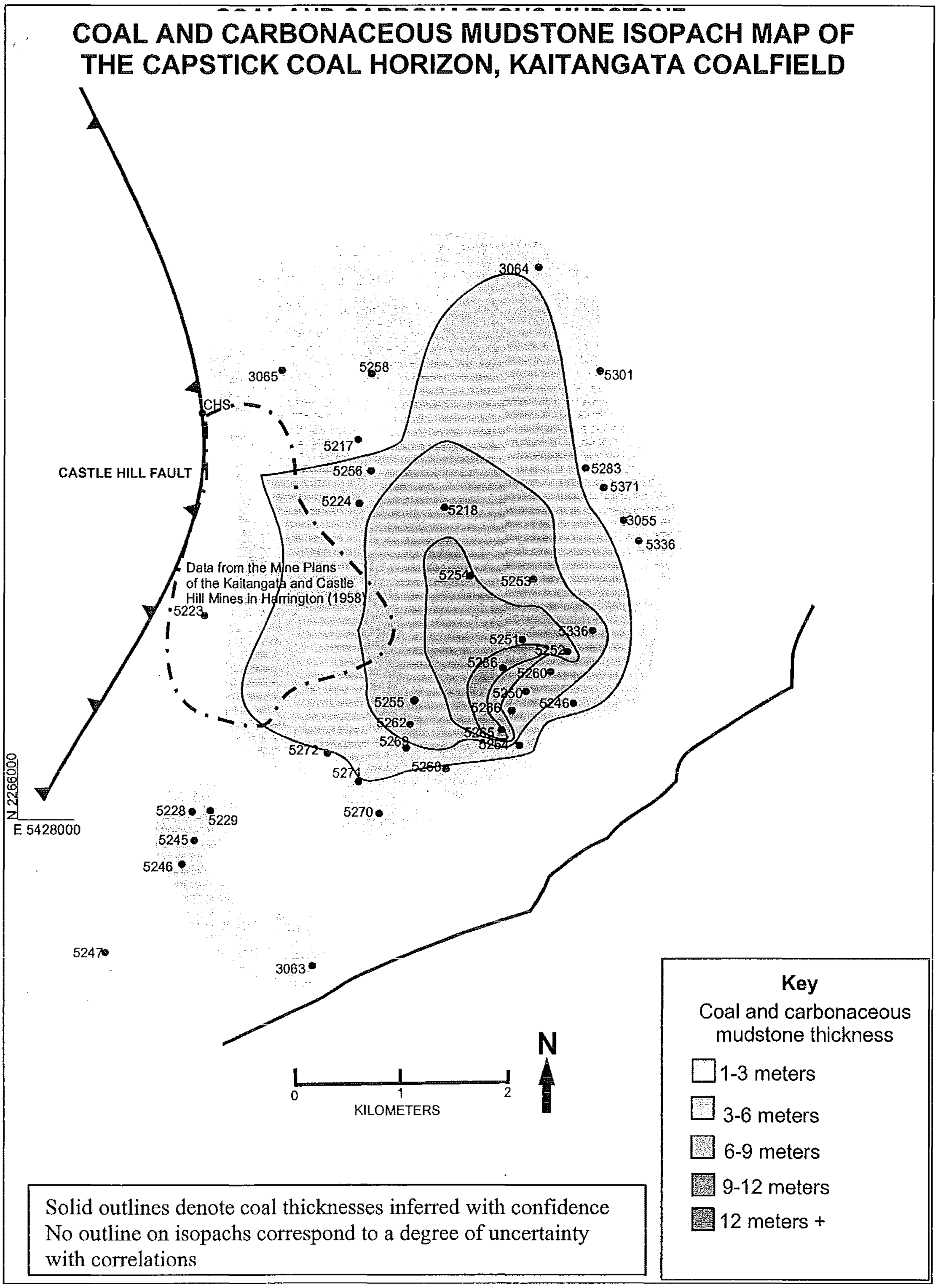
Appendix B8: Coal and carbonaceous mudstone isopach distribution for Cobweb coal horizon.



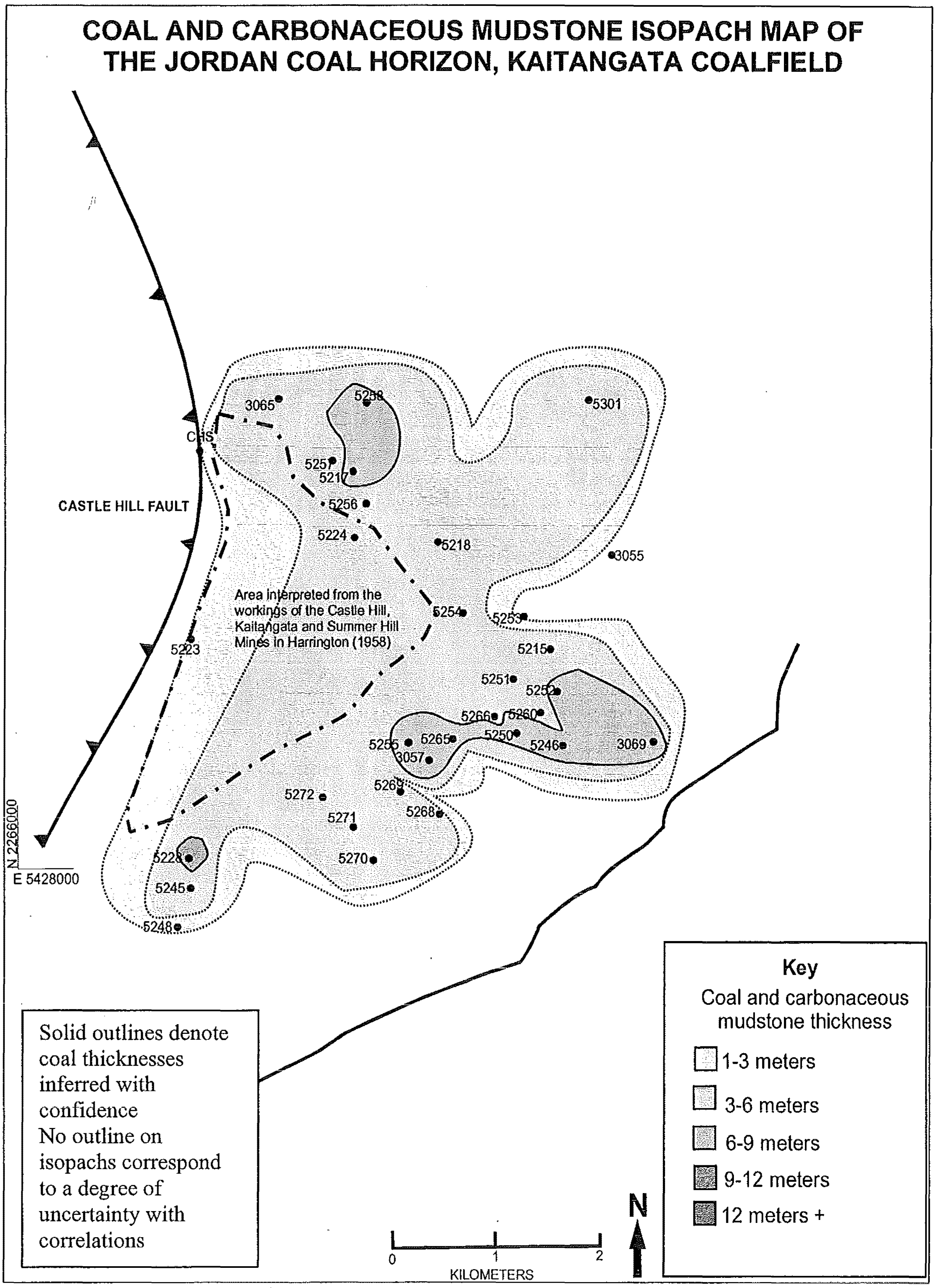
Appendix B9: Coal and carbonaceous mudstone isopach distribution for Muir coal horizon.



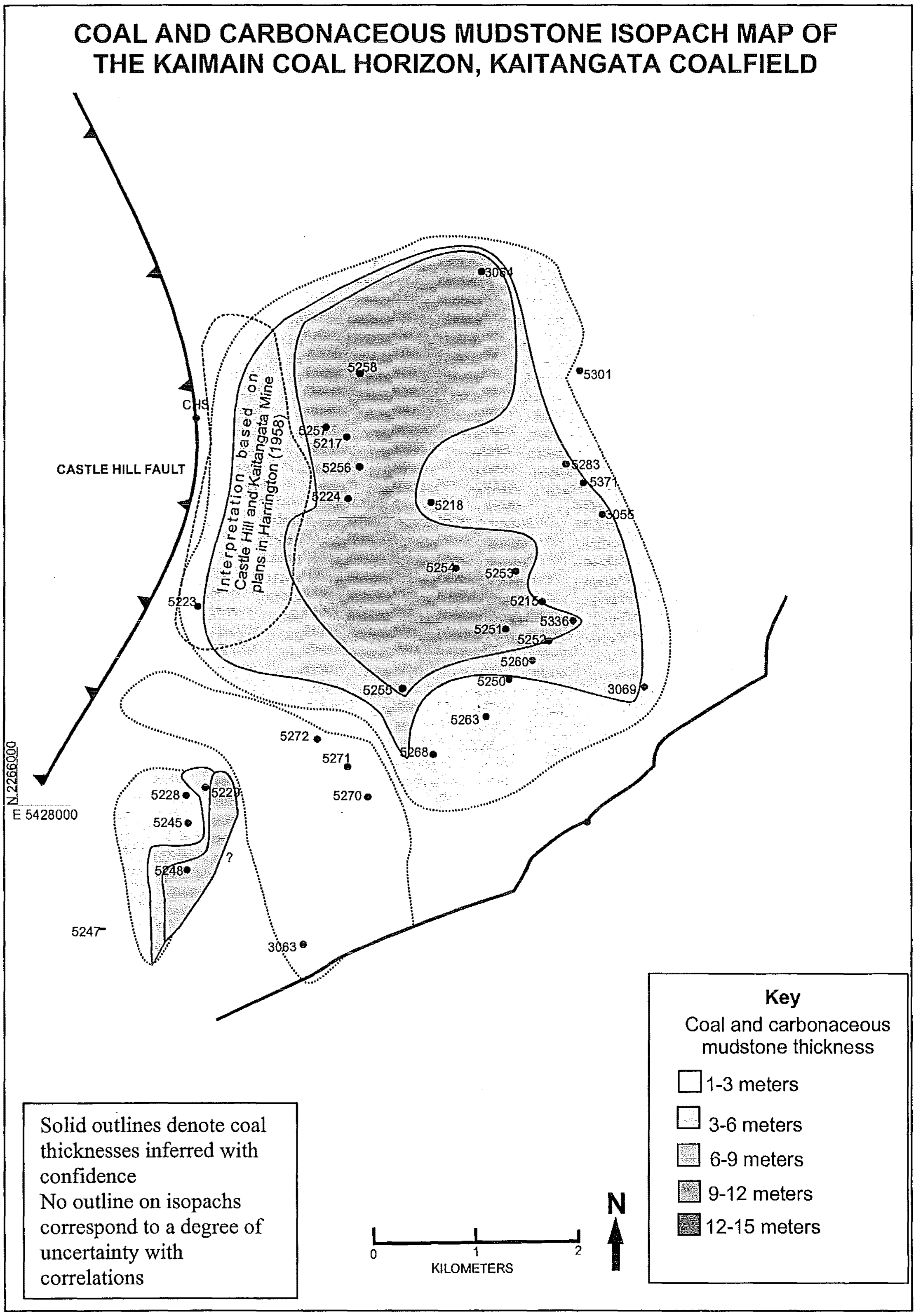
Appendix B10: Coal and carbonaceous mudstone isopach distribution for Broome coal horizon.



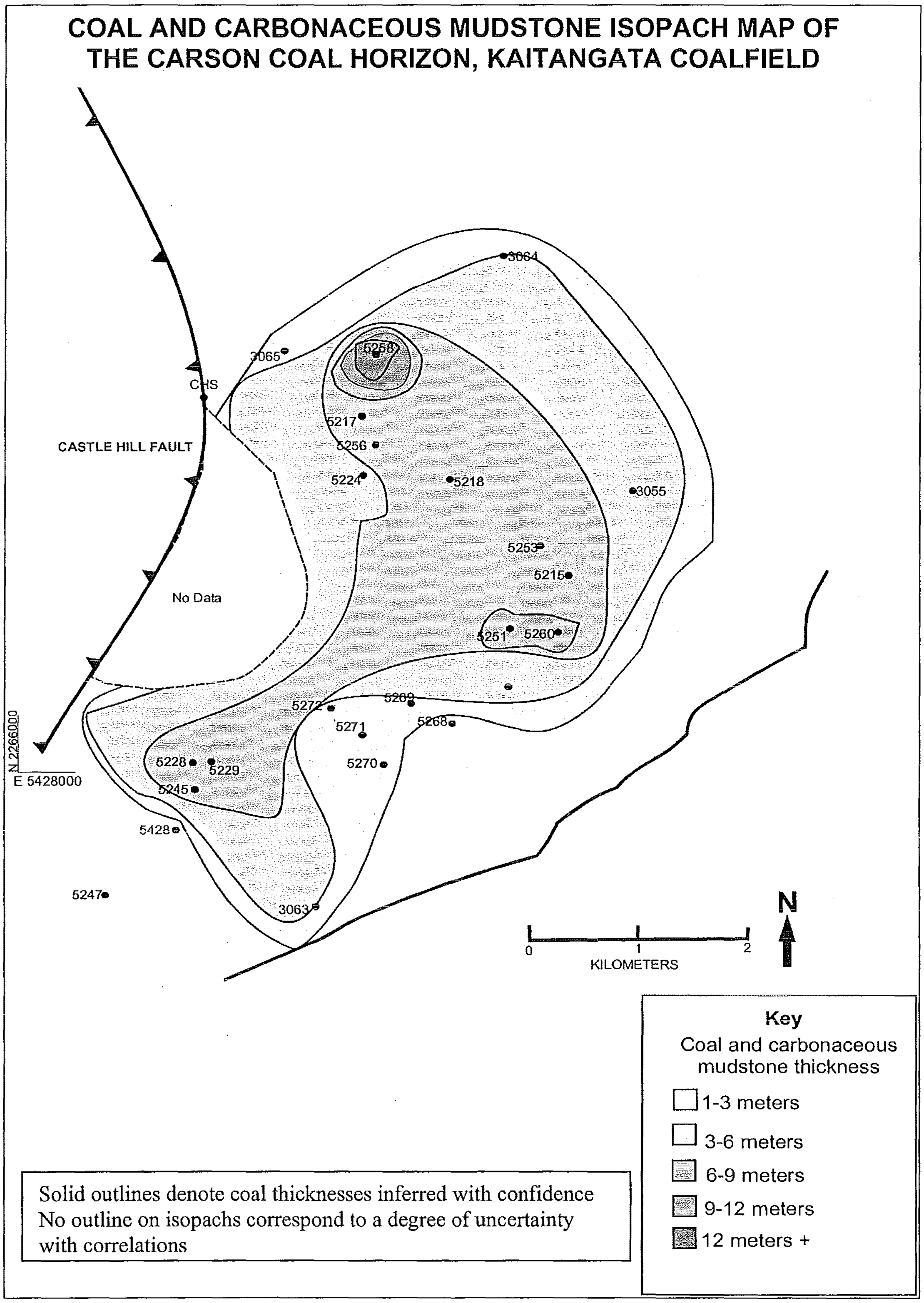
Appendix B11: Coal and carbonaceous mudstone isopach distribution for Capstick coal horizon.



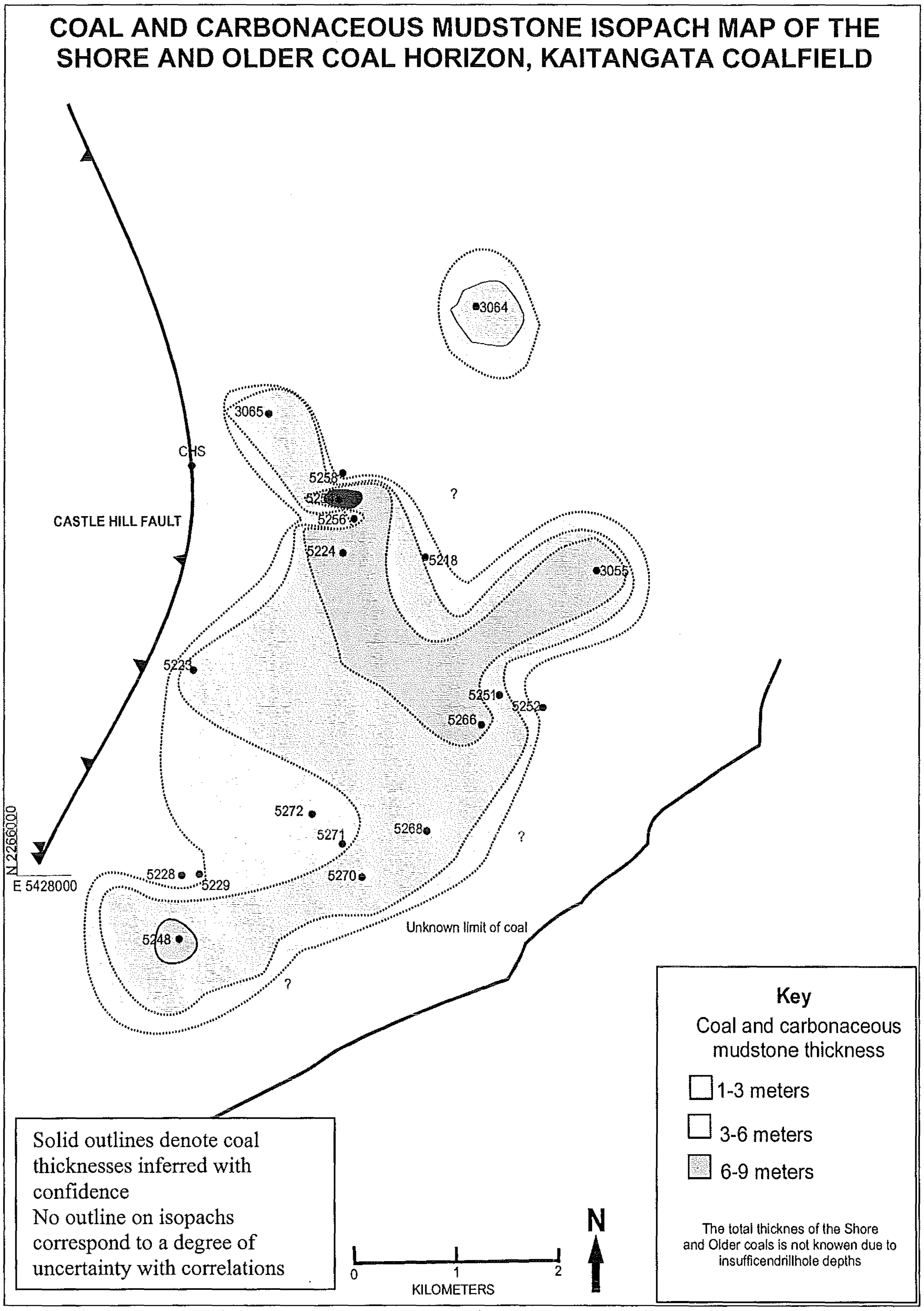
Appendix B12: Coal and carbonaceous mudstone isopach distribution for Jordan coal horizon.



Appendix B13: Coal and carbonaceous mudstone isopach distribution for Kaimain coal horizon.



Appendix B14: Coal and carbonaceous mudstone isopach distribution for Carson coal horizon.



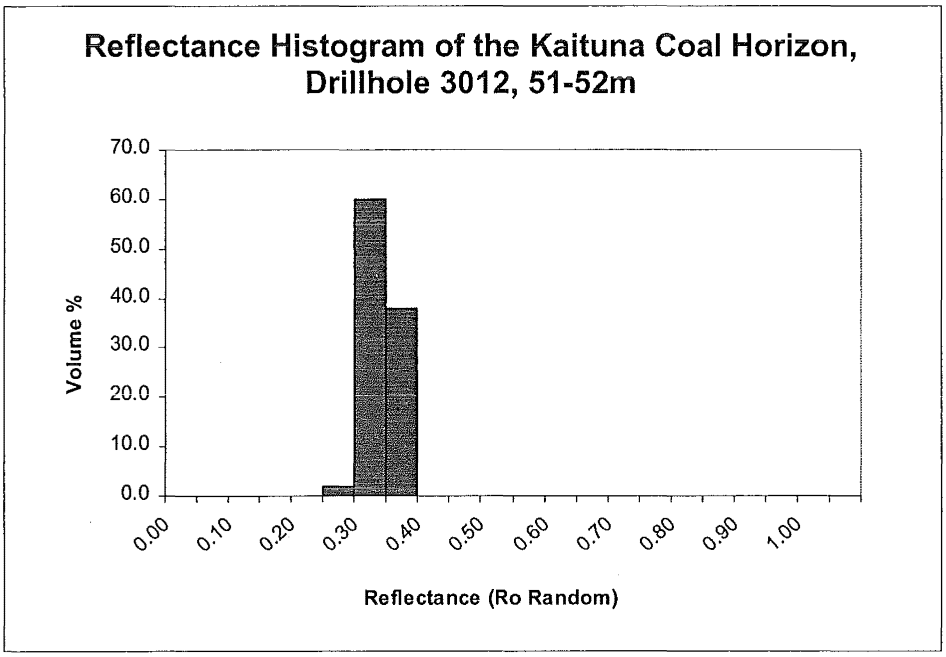
Appendix B15: Coal and carbonaceous mudstone isopach distribution for Shore and Older coal horizon.

APPENDIX C

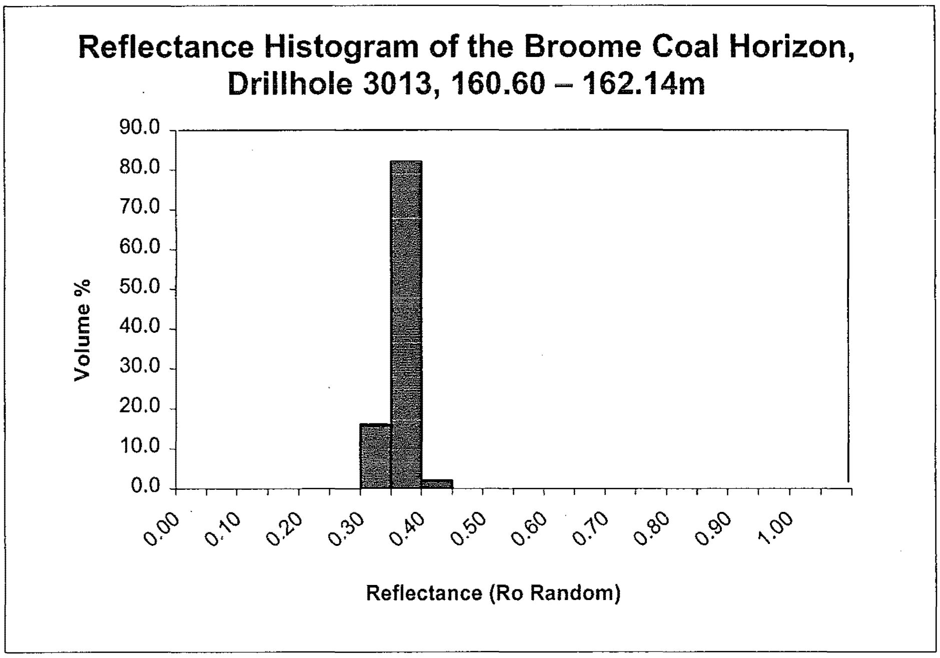
VITRINITE REFLECTANCE GRAPHS

VITRINITE REFLECTANCE GRAPHS

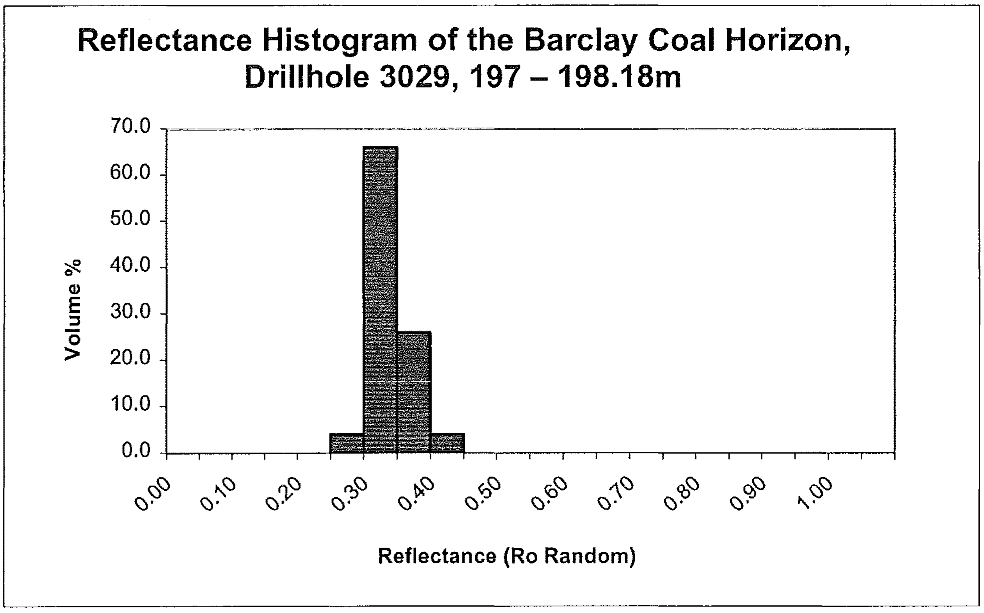
Kaitangata Sector Samples:



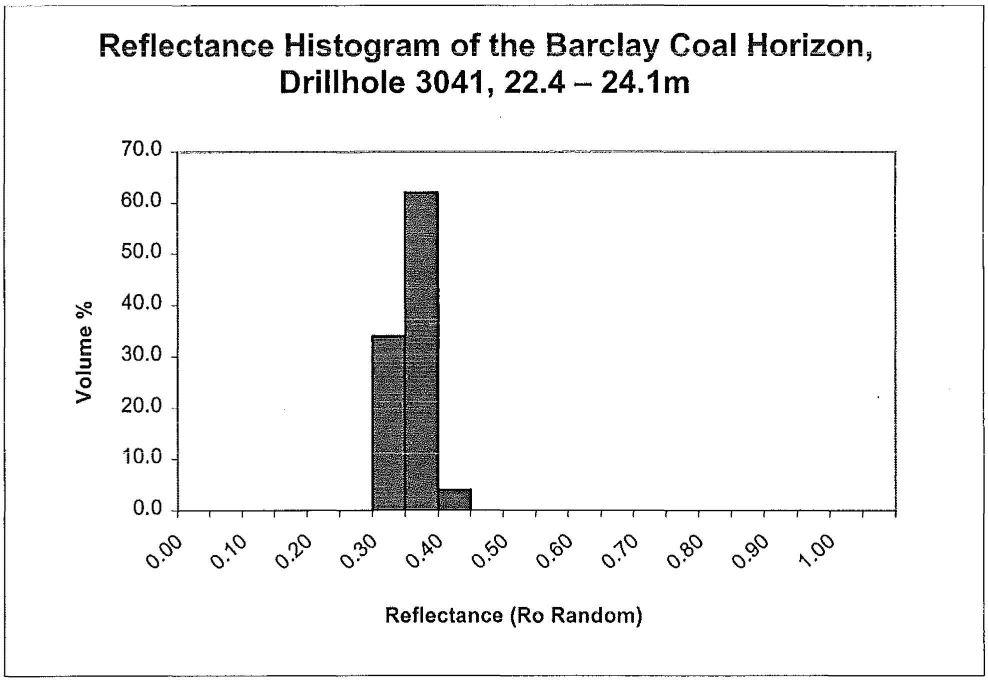
Mean Reflectance	**0.34**
Standard Deviation	**0.022**
Number of Measurements	**50**



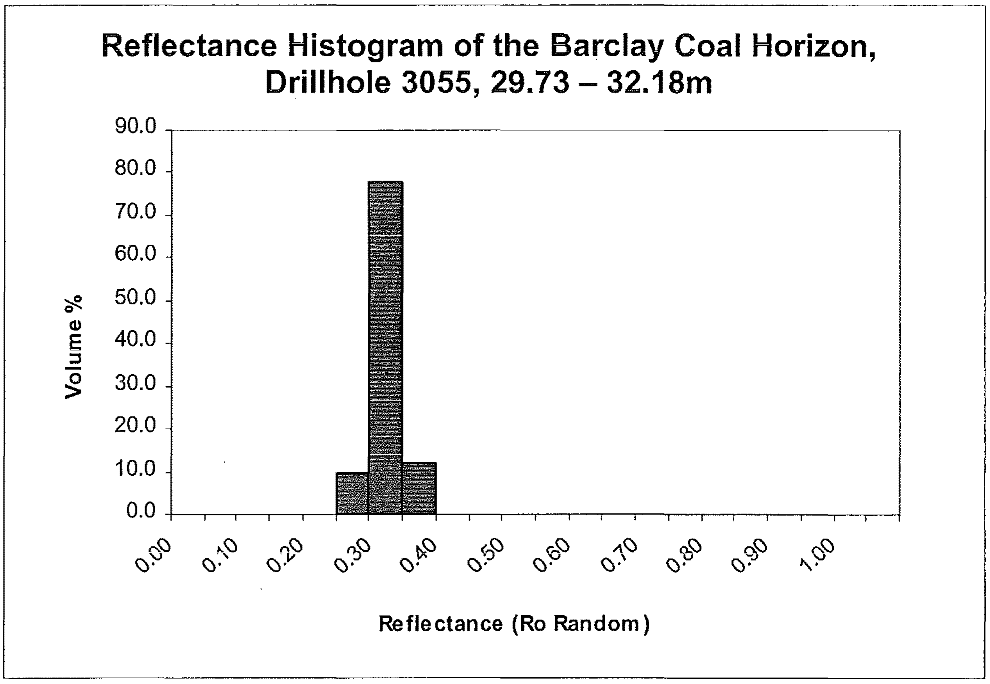
Mean Reflectance	**0.36**
Standard Deviation	**0.017**
Number of Measurements	**50**



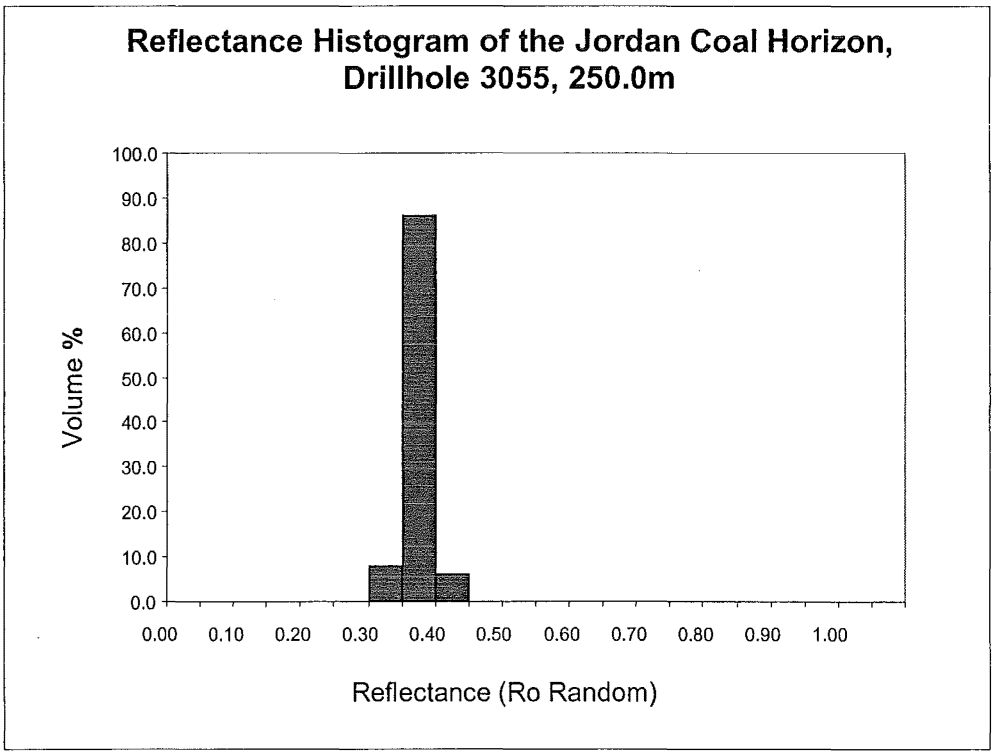
Mean Reflectance	**0.34**
Standard Deviation	**0.025**
Number of Counts	**50**



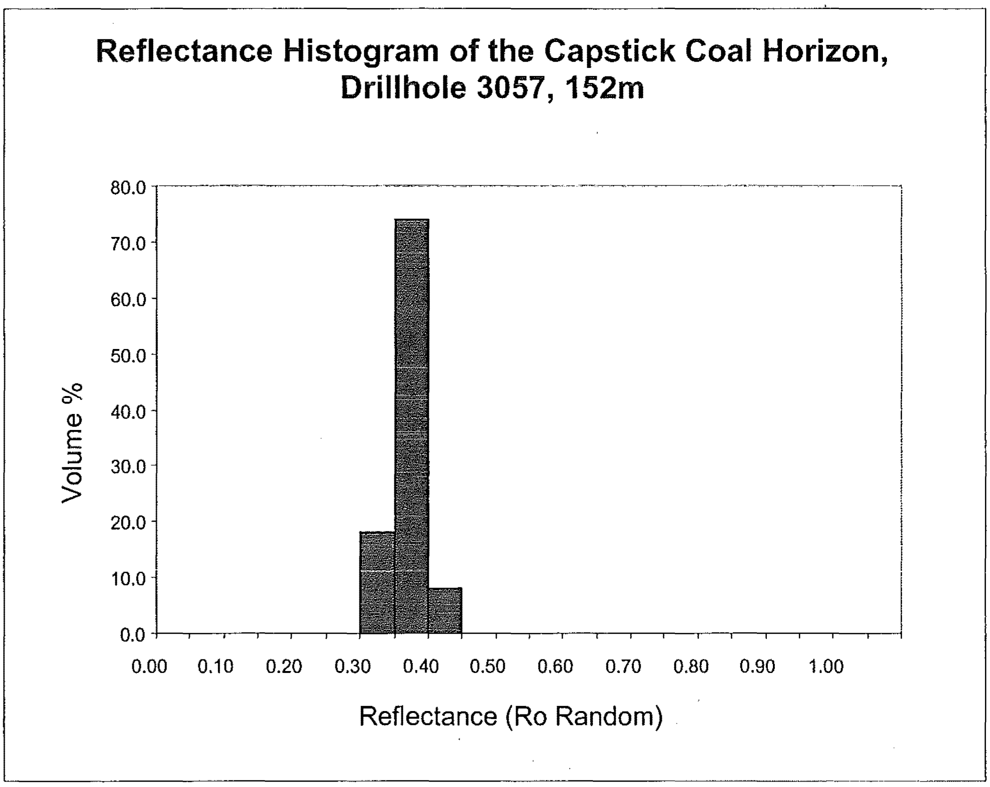
Mean Reflectance	**0.36**
Standard Deviation	**0.036**
Number of Measurements	**50**



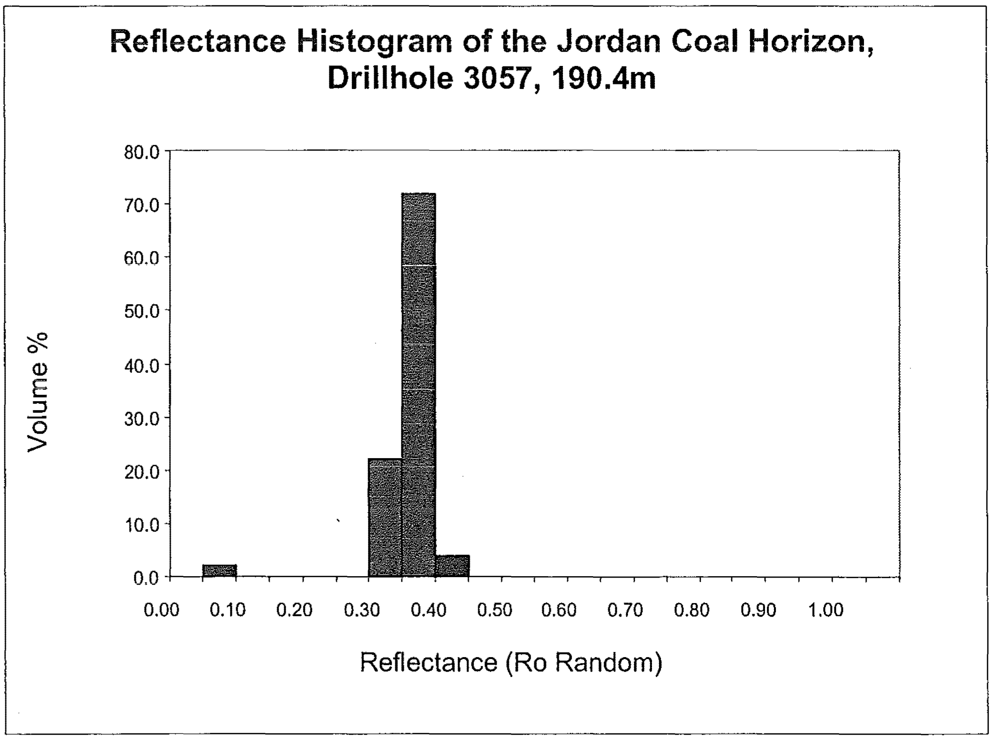
Mean Reflectance **0.33**
Standard Deviation **0.024**
Number of Measurements **50**



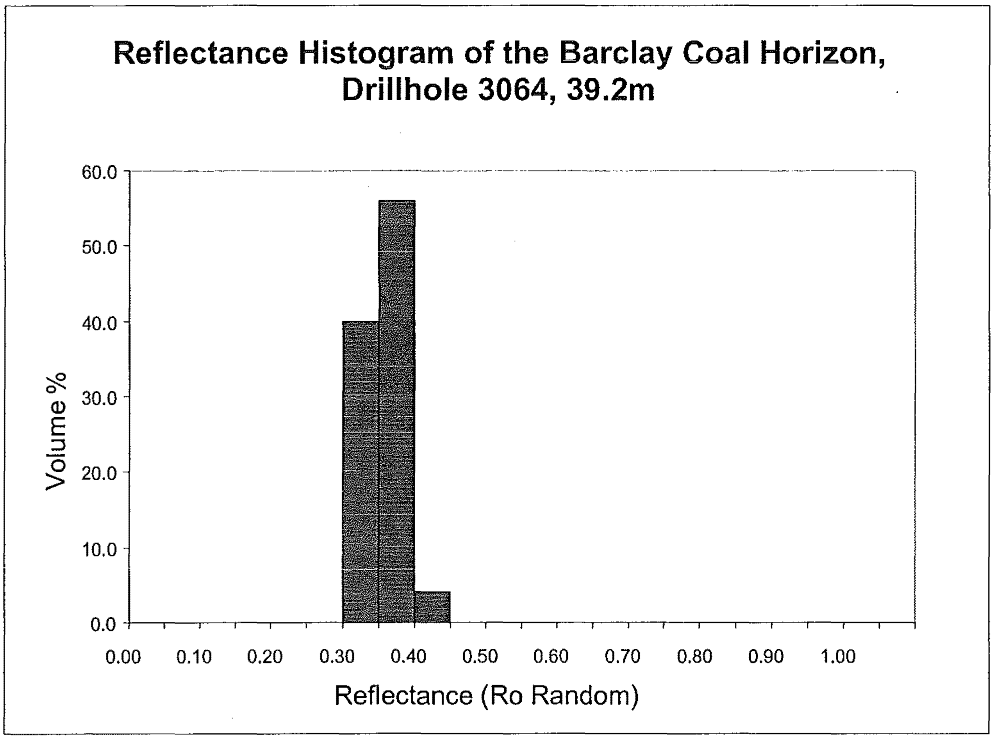
Mean Reflectance **0.41**
Standard Deviation **0.024**
Number of Measurements **50**



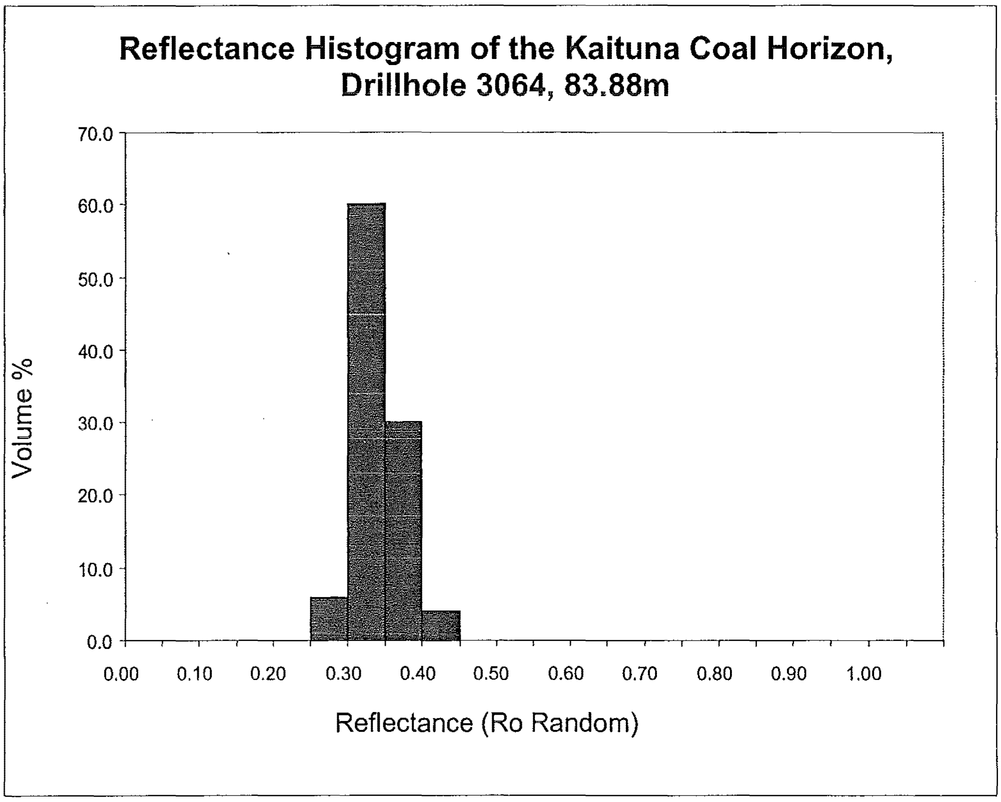
Mean Reflectance	**0.37**
Standard Deviation	**0.023**
Number of Measurements	**50**



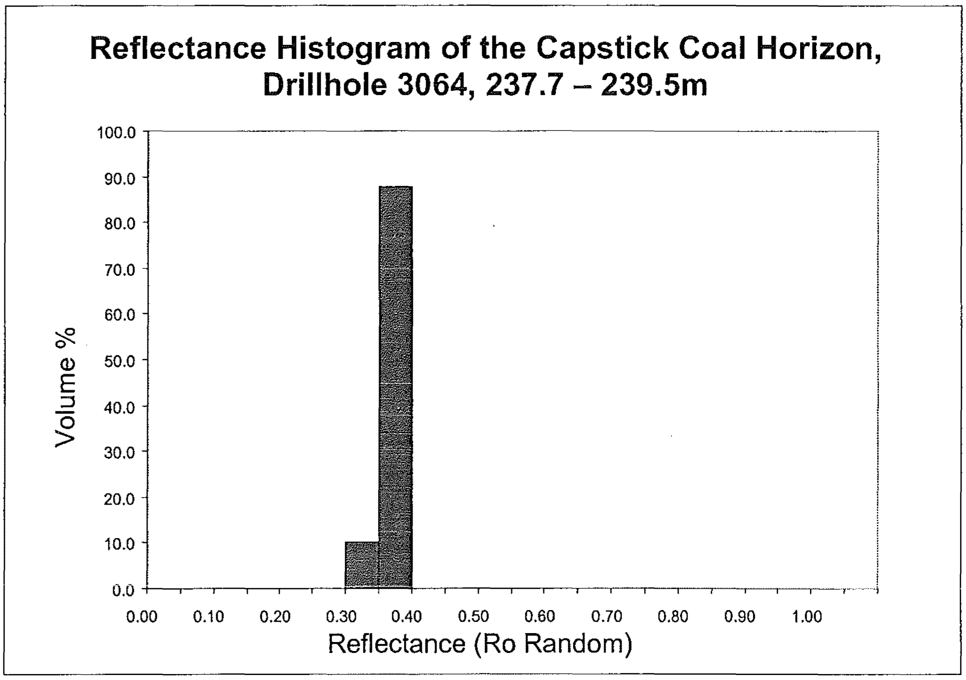
Mean Reflectance	**0.36**
Standard Deviation	**0.044**
Number of Measurements	**50**



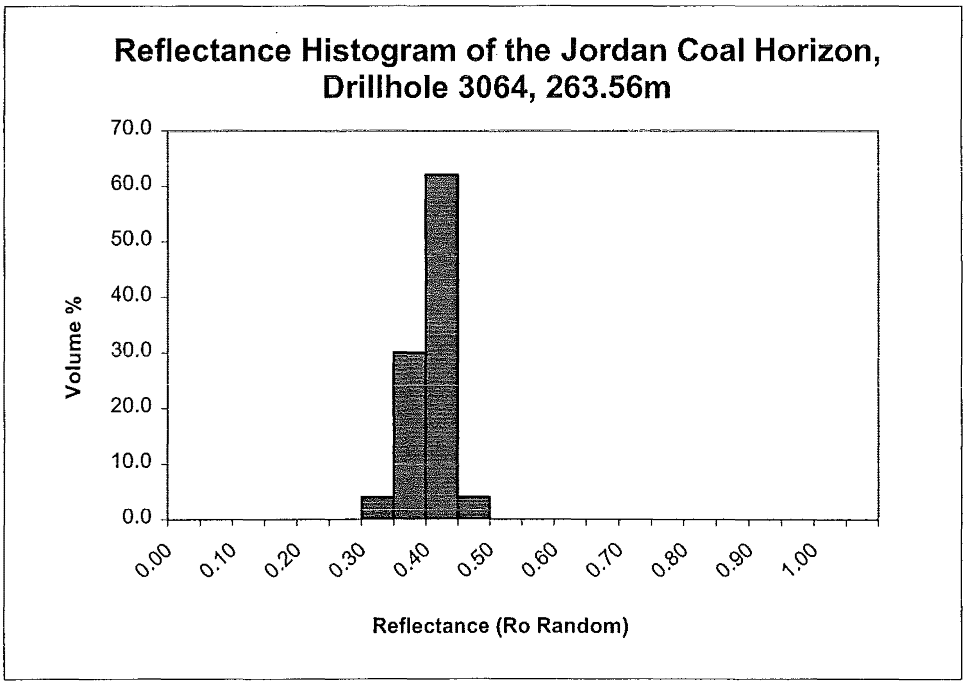
Mean Reflectance **0.36**
Standard Deviation **0.022**
Number of Measurements **50**



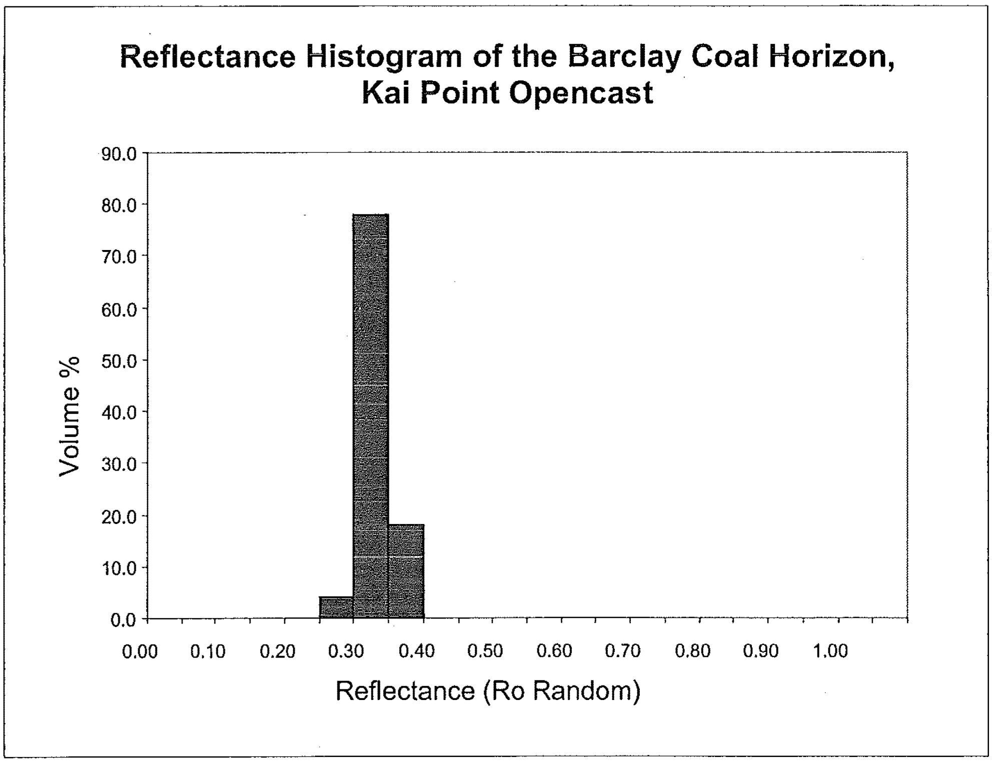
Mean Reflectance **0.34**
Standard Deviation **0.033**
Number of Measurements **50**



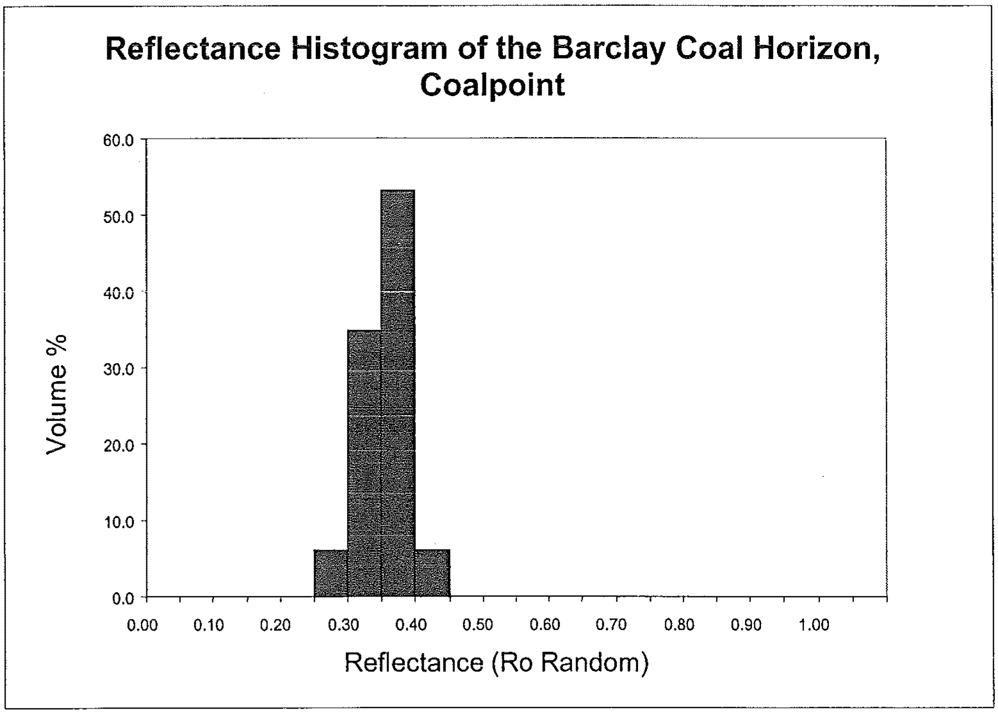
Mean Reflectance **0.39**
Standard Deviation **0.014**
Number of Measurements **50**



Mean Reflectance **0.41**
Standard Deviation **0.024**
Number of Measurements **50**

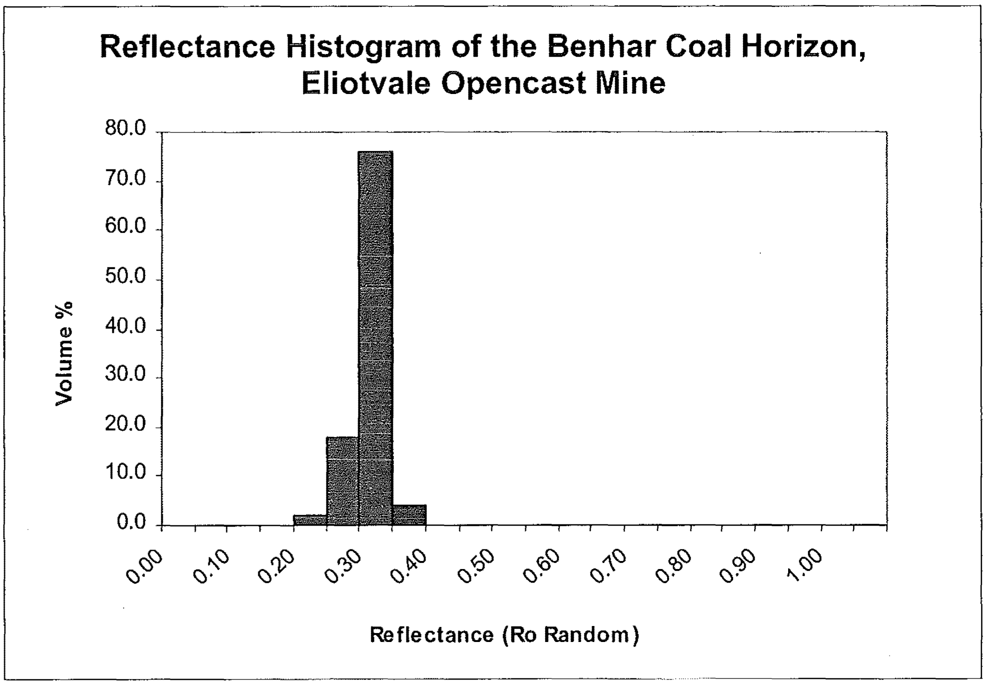


Mean Reflectance **0.33**
Standard Deviation **0.022**
Number of Measurements **50**

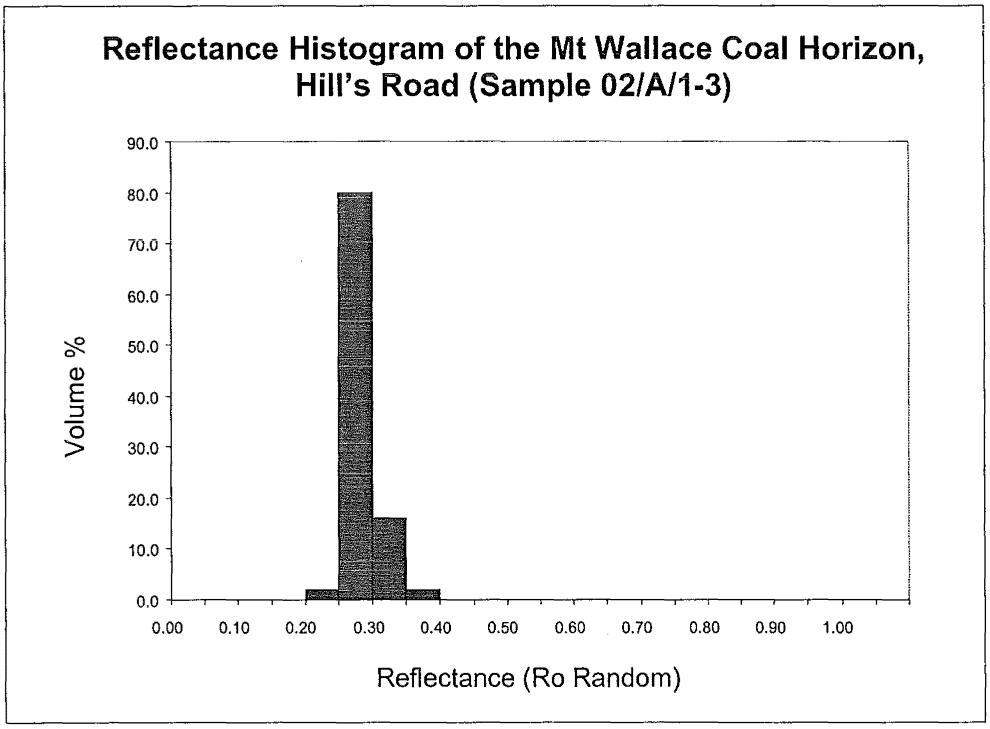


Mean Reflectance **0.37**
Standard Deviation **0.022**
Number of Measurements **50**

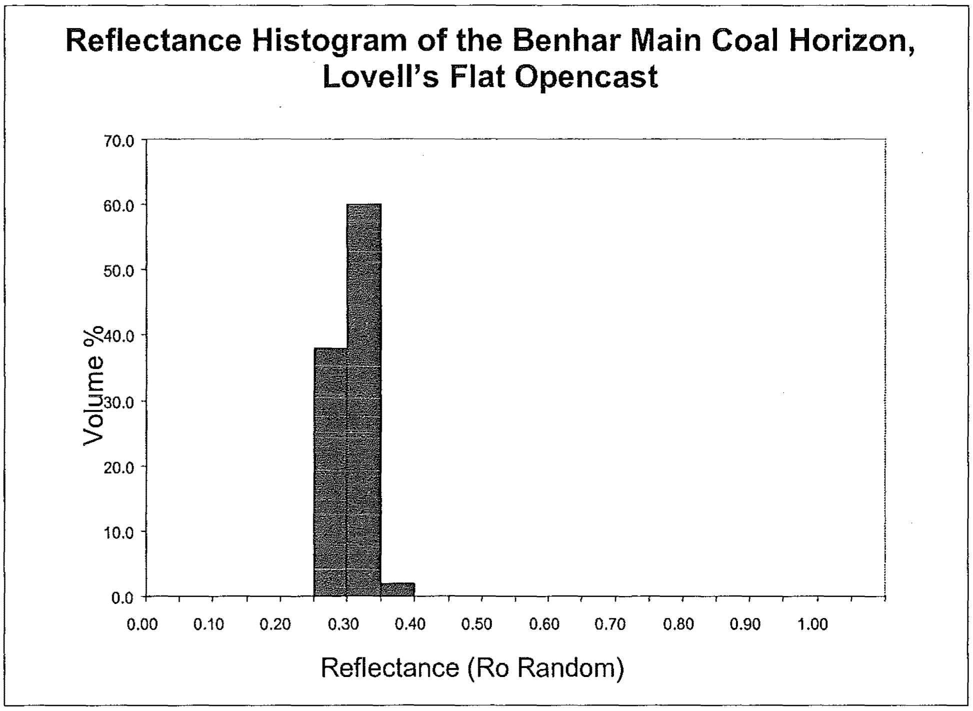
Benhar Sector Samples:



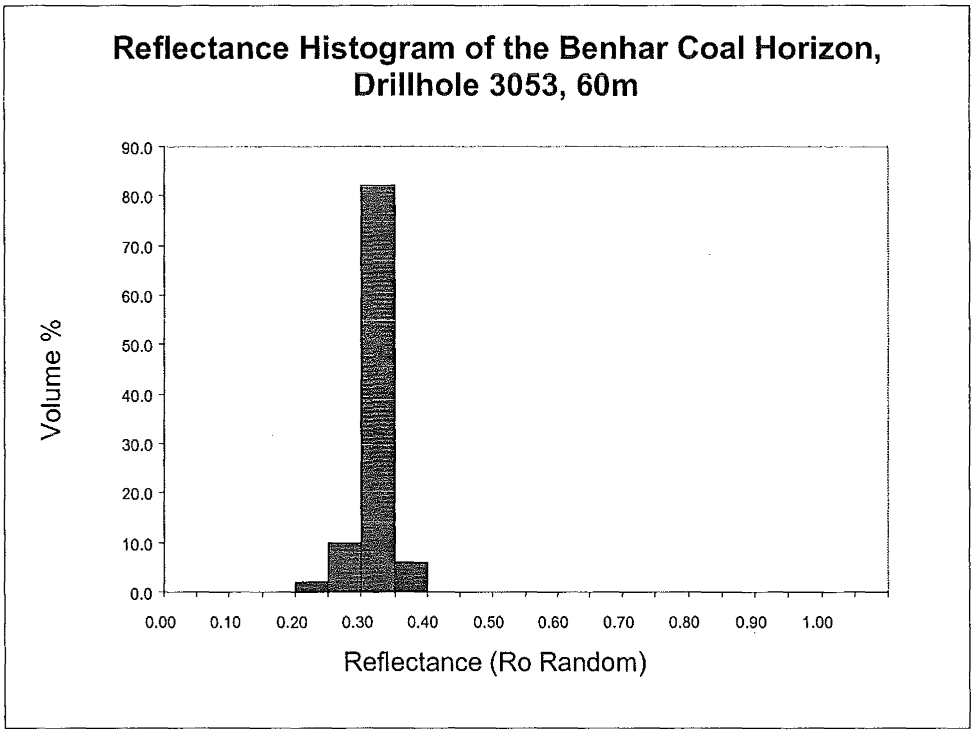
Mean Reflectance	**0.37**
Standard Deviation	**0.016**
Number of Measurements	**50**



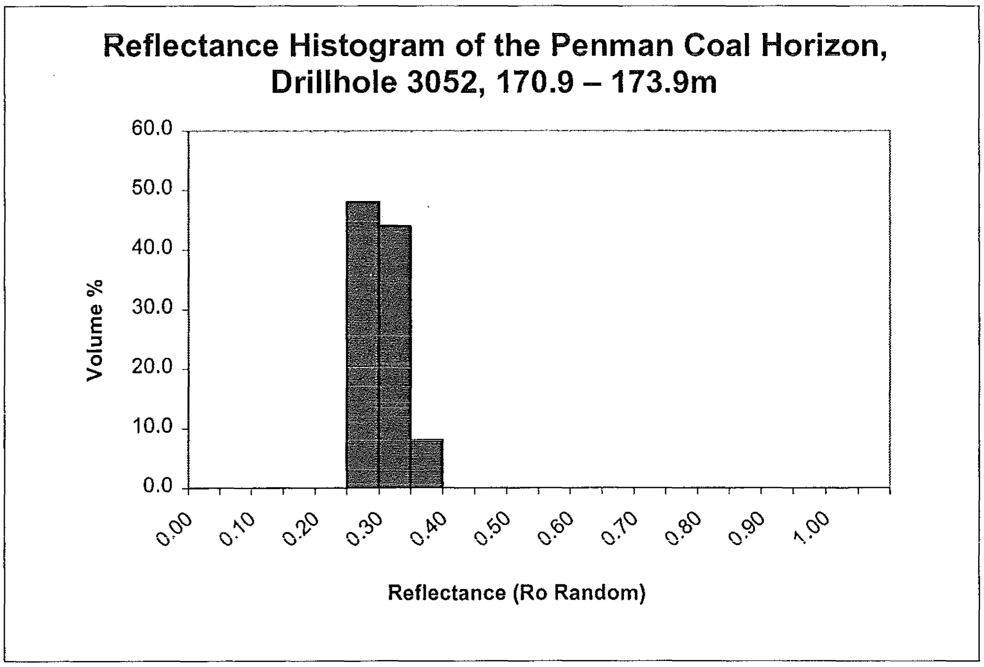
Mean Reflectance	**0.28**
Standard Deviation	**0.020**
Number of Measurements	**50**



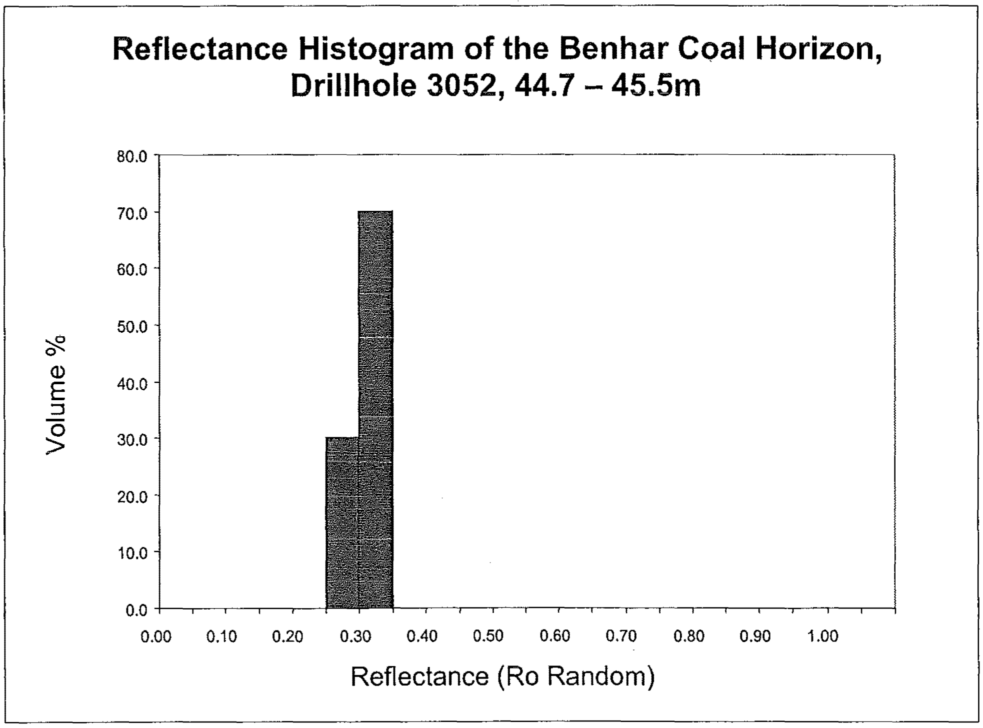
Mean Reflectance **0.32**
Standard Deviation **0.025**
Number of Measurements **50**



Mean Reflectance **0.32**
Standard Deviation **0.022**
Number of Measurements **50**

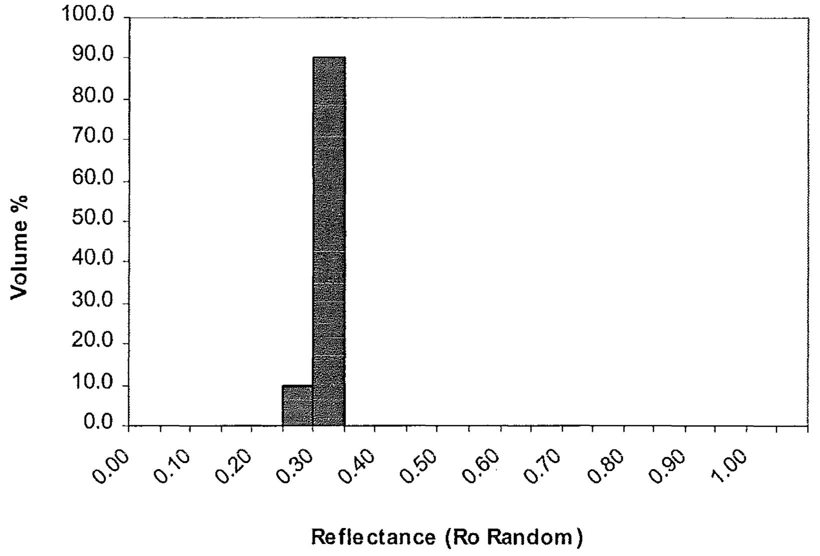


Mean Reflectance 0.33
Standard Deviation 0.26
Number of Measurements 50



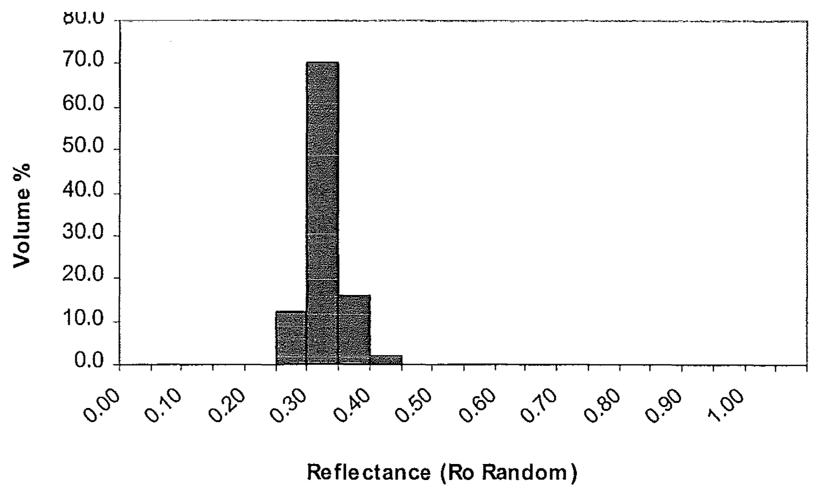
Mean Reflectance 0.30
Standard Deviation 0.22
Number of Measurements 50

Reflectance Histogram of the Benhar Main Coal Horizon, Drillhole 3050. 70.9 – 74.0m

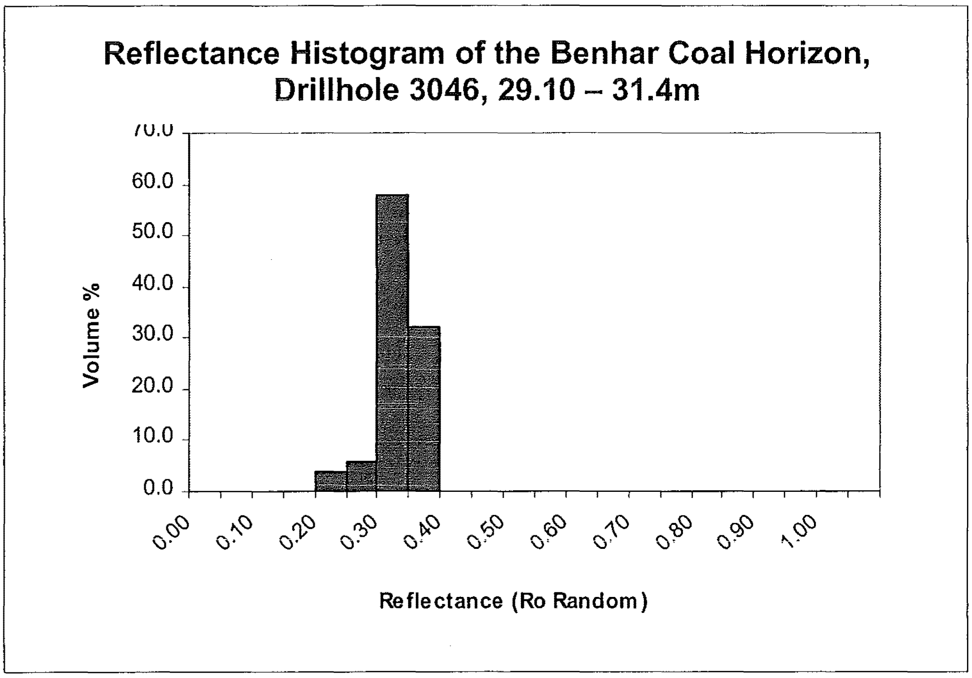


Mean Reflectance **0.33**
Standard Deviation **0.015**
Number of Measurements **50**

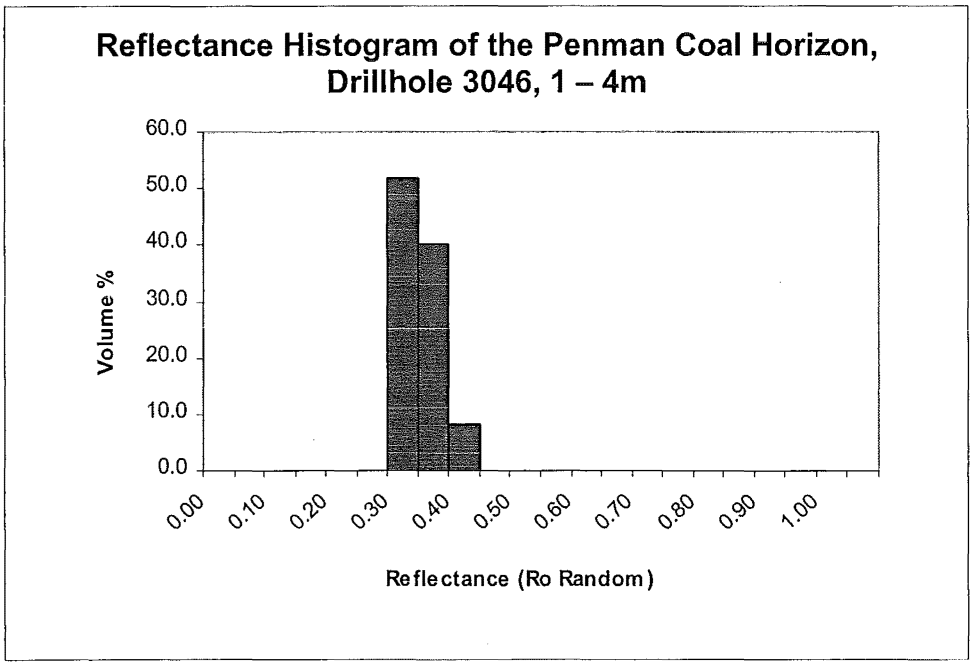
Reflectance Histogram of the Penman Coal Horizon, Drillhole 3050, 181.2 – 181.7m



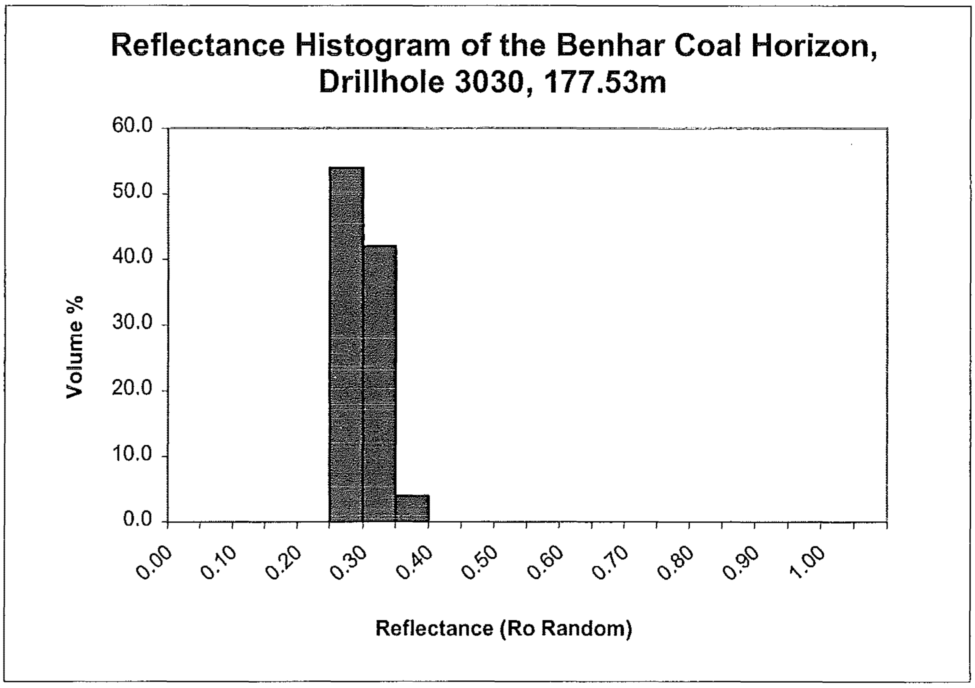
Mean Reflectance **0.33**
Standard Deviation **0.027**
Number of Measurements **50**



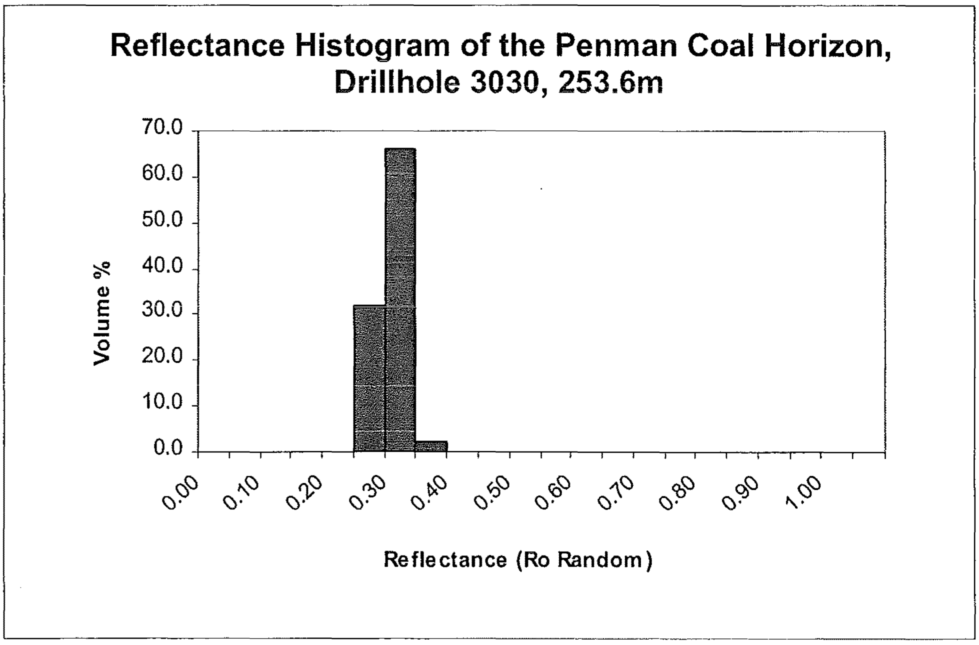
Mean Reflectance **0.33**
Standard Deviation **0.034**
Number of Measurements **50**



Mean Reflectance **0.35**
Standard Deviation **0.027**
Number of Measurements **50**



Mean Reflectance **0.30**
Standard Deviation **0.025**
Number of Measurements **50**



Mean Reflectance **0.33**
Standard Deviation **0.020**
Number of Measurements **50**

APPENDIX D

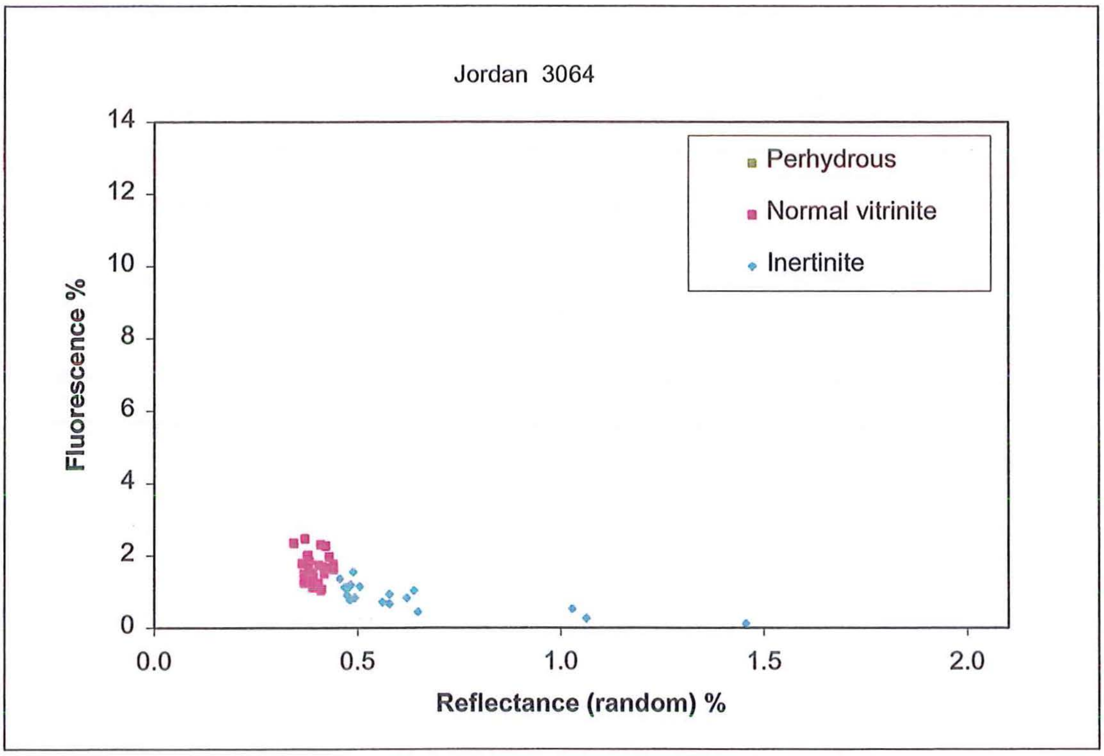
VITRINITE AND INERTINITE REFLECTANCE FLUORESCENCE (VIRF)

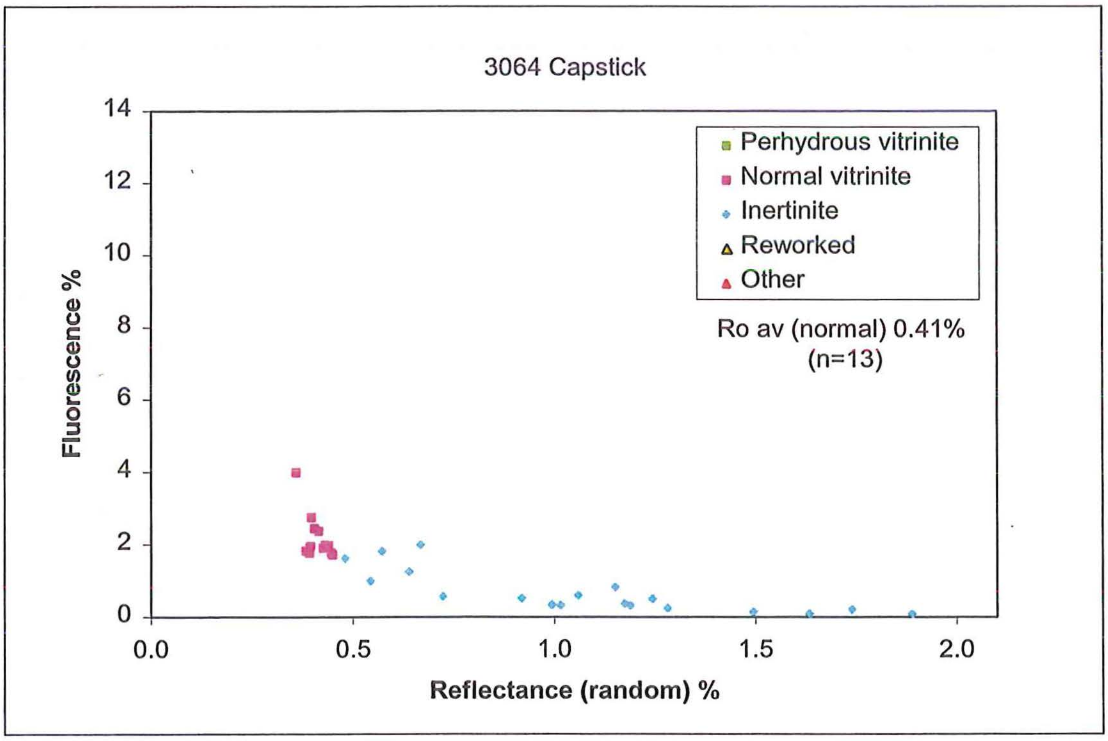
VIRF ANALYSIS

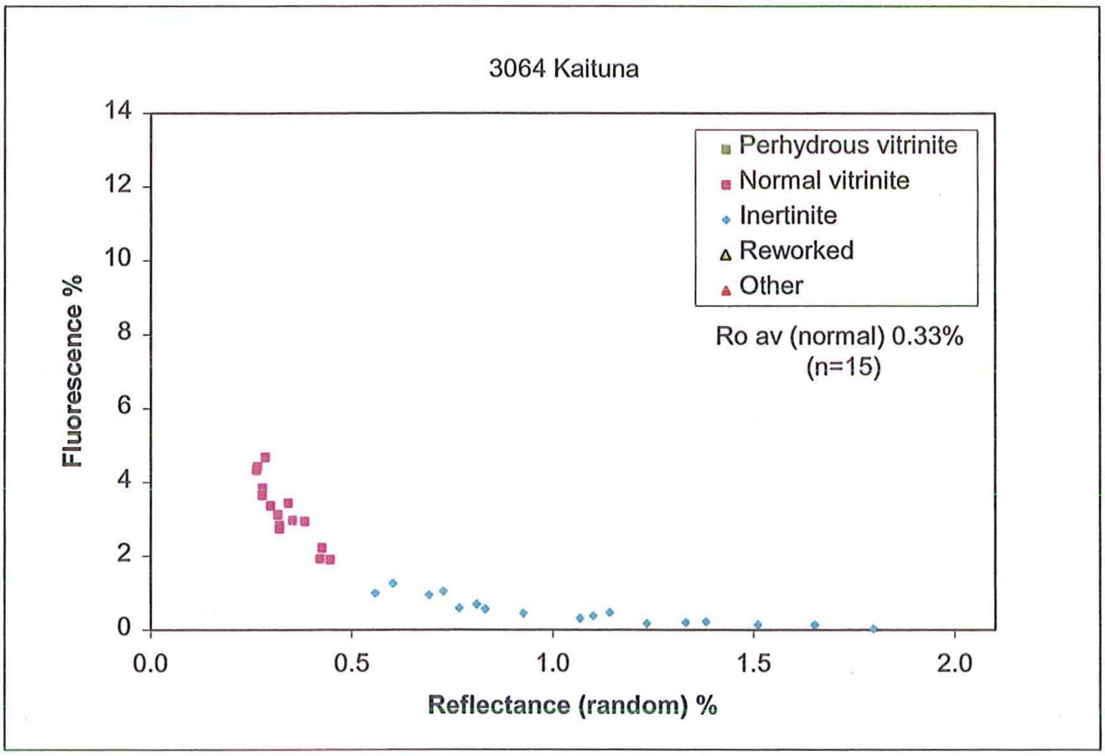
Vitrinite and Inertinite Reflectance Fluorescence (VIRF) analyses were preformed by Dr. Jane Newman and Nick Moore of Newman Industries Ltd.

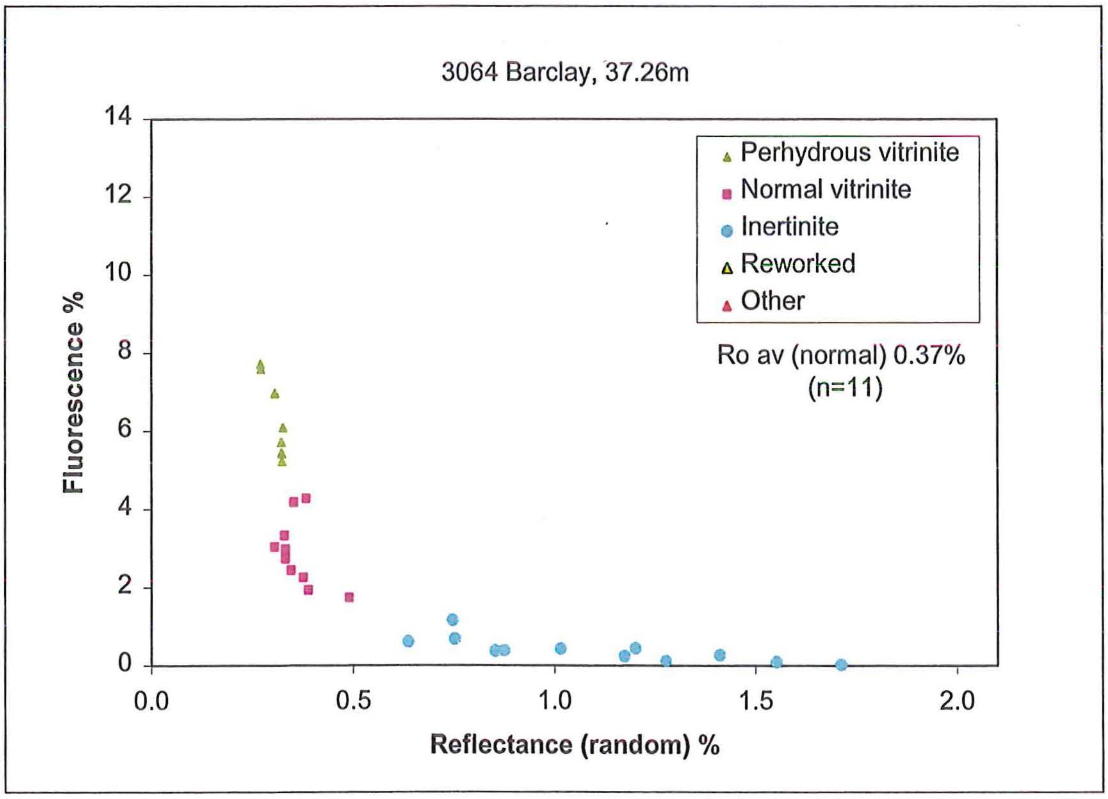
VIRF analyses showed that there were discrete transitions between telovitrinite and semifusinite in the Jordan and Capstick members. The transition from telovitrinite-semifusinite occurs between 0.35-0.44% Ro random, with a mean of 0.40% Ro random. In contrast, the Barclay and Kaituna samples reflectance range for the transition of telovitrinite to semifusinite was very small, with 0.29-0.34% Ro random with a mean of 0.33% Ro random.

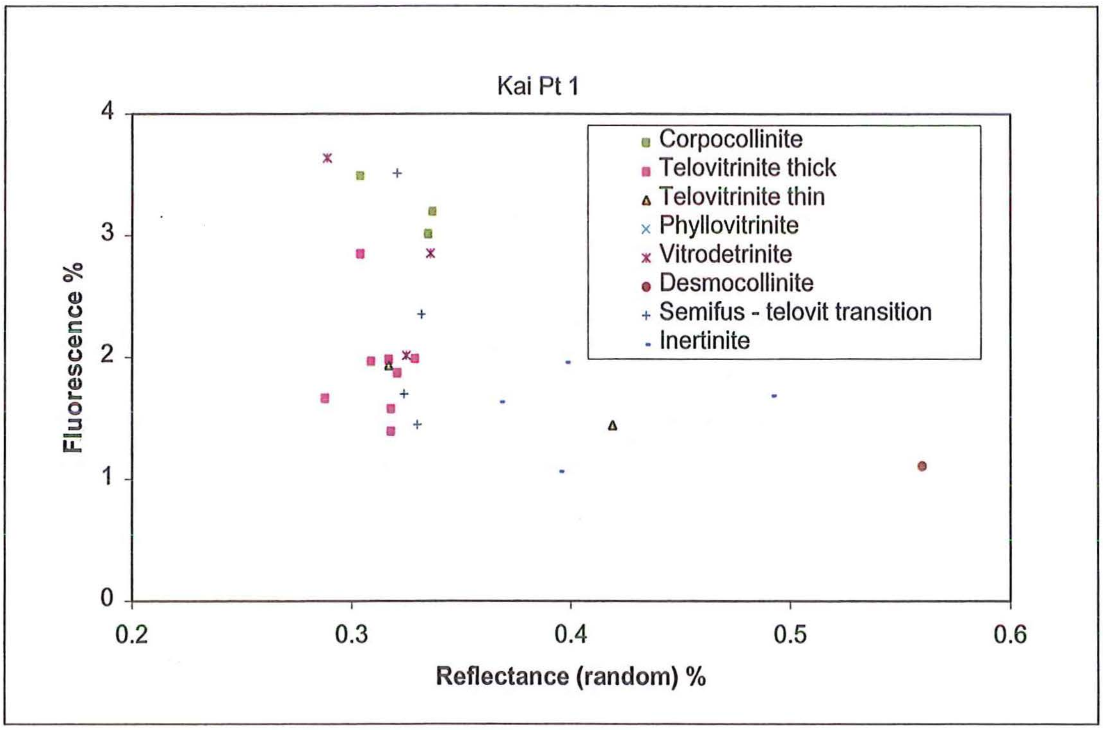
There is a minor component of perhydrous vitrinite evident in the Barclay seam in drillhole 3064. However, the percentage of perhydrous vitrinites were not significant enough to affect the measurement of telovitrinite for vitrinite reflectance analysis.

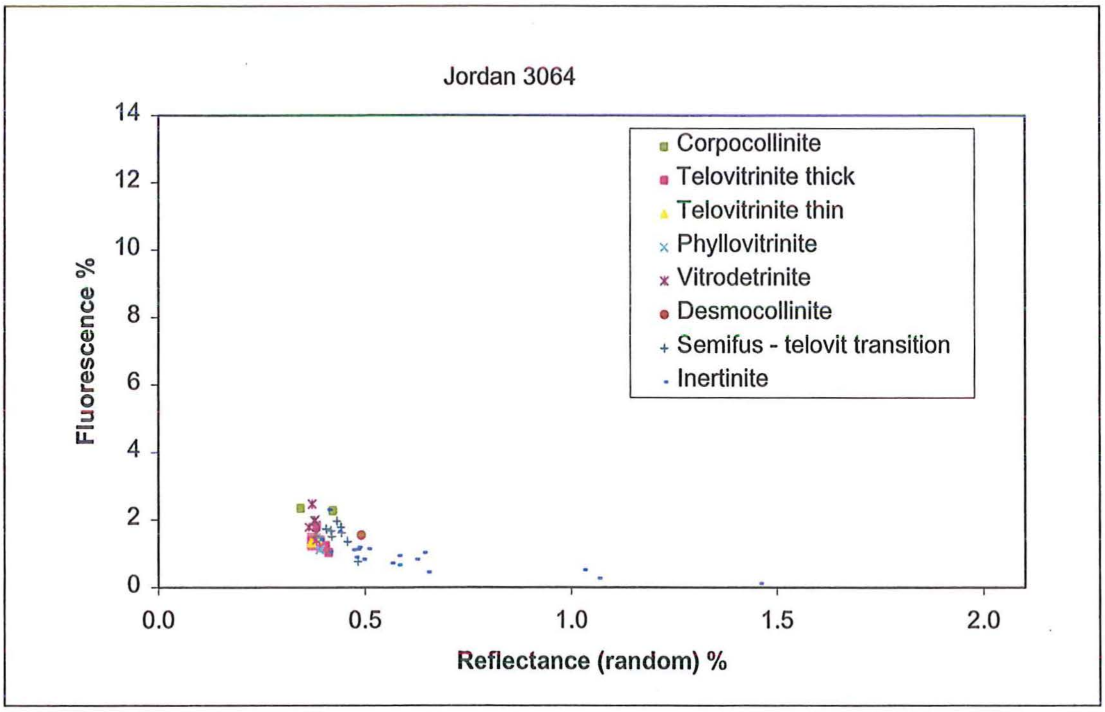

Jordan 3064
Perhydrous
Normal vitrinite
Inertinite
Fluorescence %
Reflectance (random) %
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0

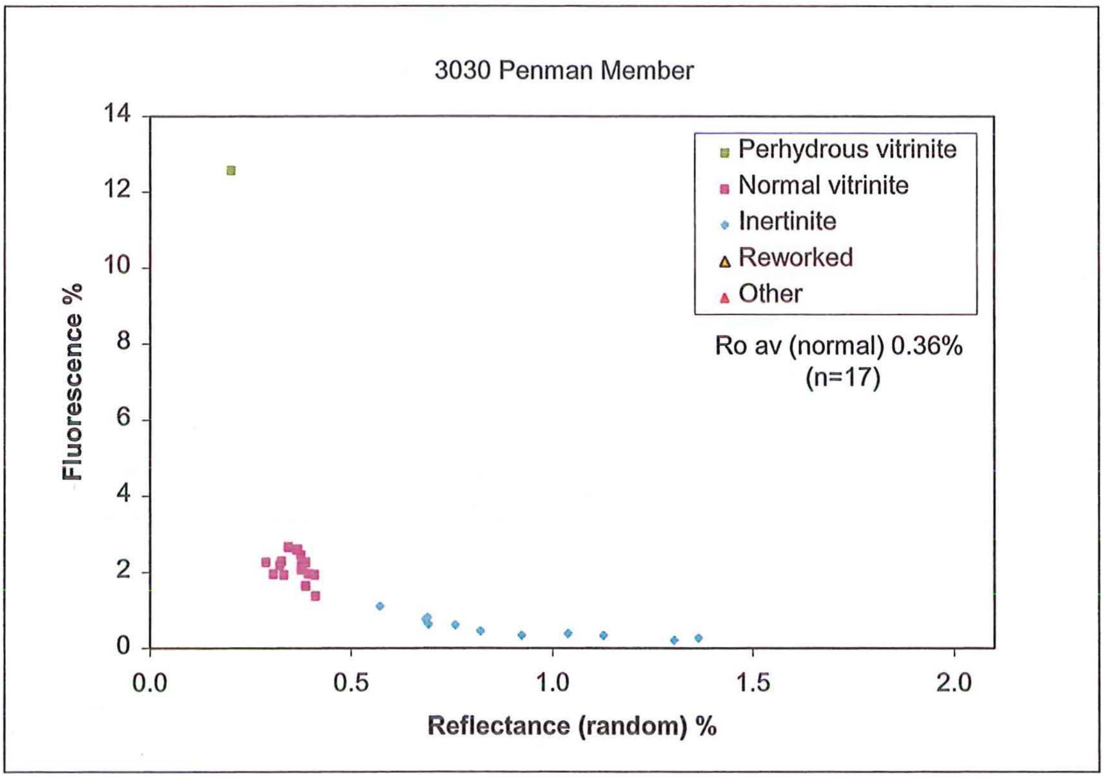

3064 Capstick
Perhydrous vitrinite
Normal vitrinite
Inertinite
Reworked
Other
Ro av (normal) 0.41%
(n=13)
Fluorescence %
Reflectance (random) %
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0

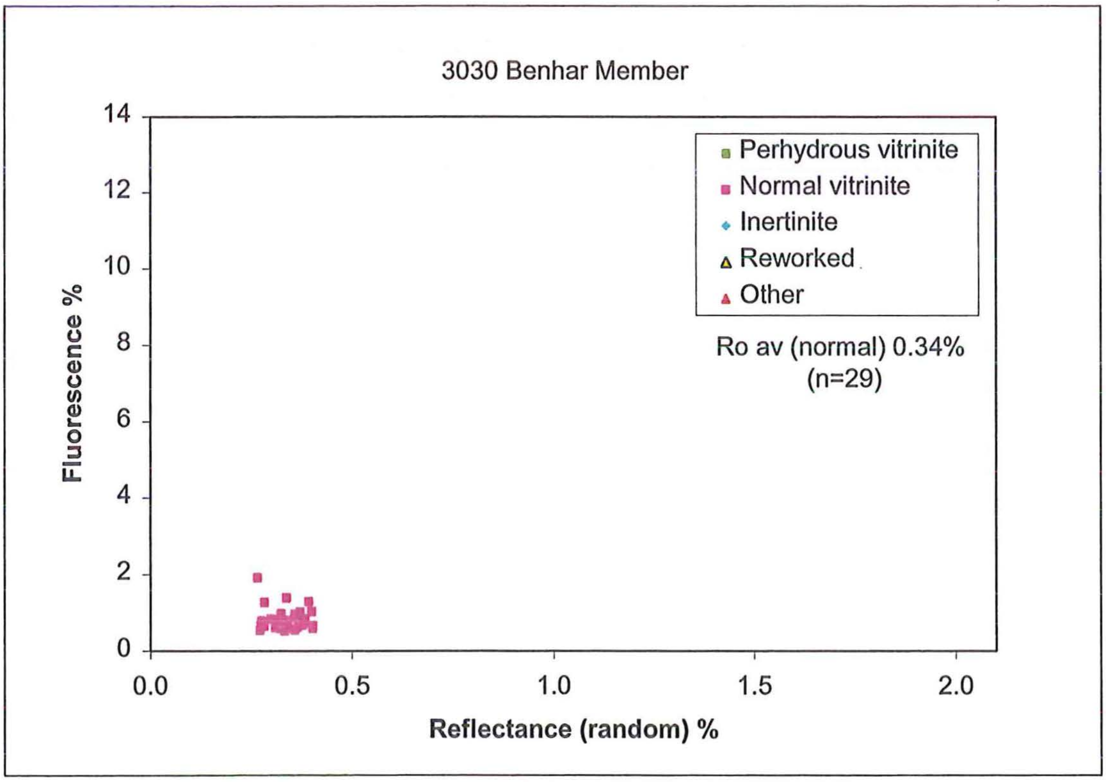

3064 Kaituna
Perhydrous vitrinite
Normal vitrinite
Inertinite
Reworked
Other
Ro av (normal) 0.33%
(n=15)
Fluorescence %
Reflectance (random) %
0
2
4
6
8
10
12
14
0.0
0.5
1.0
1.5
2.0


3064 Barclay, 37.26m
Perhydrous vitrinite
Normal vitrinite
Inertinite
Reworked
Other
Ro av (normal) 0.37%
(n=11)
Fluorescence %
Reflectance (random) %
0
2
4
6
8
10
12
14
0.0
0.5
1.0
1.5
2.0


Kai Pt 1
Corpocollinite
Telovitrinite thick
Telovitrinite thin
Phyllovitrinite
Vitrodetrinite
Desmocollinite
Semifus - telovit transition
Inertinite
Fluorescence %
Reflectance (random) %
0
1
2
3
4
0.2
0.3
0.4
0.5
0.6


Jordan 3064
Corpocollinite
Telovitrinite thick
Telovitrinite thin
Phyllovitrinite
Vitrodetrinite
Desmocollinite
Semifus - telovit transition
Inertinite
Fluorescence %
Reflectance (random) %
0
2
4
6
8
10
12
14
0.0
0.5
1.0
1.5
2.0


3030 Penman Member
Fluorescence %
Reflectance (random) %
Perhydrous vitrinite
Normal vitrinite
Inertinite
Reworked
Other
Ro av (normal) 0.36%
(n=17)
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0


3030 Benhar Member
Fluorescence %
Reflectance (random) %
Perhydrous vitrinite
Normal vitrinite
Inertinite
Reworked
Other
Ro av (normal) 0.34%
(n=29)
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0

APPENDIX E

DATA CD (CD pocket at back of thesis)

- COAL CHEMISTRY DATABASE
- LOGPLOT STRATIGRAPHIC COLUMNS
- PDF. STRATIGRAPHIC COLUMNS

Appendix E

Data Compact Disc

The data CD ROM is divided into two folders that relate to the stratigraphy and rank trend analyses within this MSc. Thesis.

A: Stratigraphic Columns Folder

This is a database of all drillholes that have been analysed for stratigraphic purposes. It is further subdivided into to sections; 1) Logplot Files of Drillholes; 2) PDF files of Drillholes.

1) Logplot Files

This folder contains files that can be opened using the Rockware programme 'Logplot 2000'. These are stratigraphic columns of drillholes analysed in the Kaitangata Coalfield and are saved as .dat files, which will be recognized by the Logplot programme. There is also a folder of .pat files, which are all the lithology patterns used in this thesis (described in Table 2.1,). These logs can be viewed at multiple scales so that different levels of information can be obtained. There are also attached spreadsheets, which give detail about any additional structure or important drillers notes.

2) Logplot PDF Files

This folder contains stratigraphic logs completed in the Rockware Programme 'Logplot 2000'. These logs are pdf. reproductions of the same logs in the Logplot Folder, but can be viewed through any drawing programme. Due to size constraints, these logs show less detail, and do not have drillers logs attached.

B: Coal Geochemistry Database

This is a speadsheet of all the summarised proximate and ultimate analytical data for drillholes in the Kaitangata Coalfield. This enables all raw data of analyses completed in this thesis to be viewed. Formulas for coal chemistry corrections are active and can be adjusted to allow for different correction factors if necessary. Not every type of analysis has been completed on each drillhole, so there are some blank cells. The format and macros for the coal geochemistry spreadsheets, were written by Richard Sykes at the Geological and Nuclear Sciences Centre.

APPENDIX F

LOCATION OF DRILLHOLE AND OUTCROP SAMPLES

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
6022	2099	2264067.50	5597872.50	0.00	Unknown
6621	3000	2266291.25	5446705.50	0.00	Unknown
6623	3001	2266348.20	5442958.60	24.40	13/10/1981
6625	3002	2264894.00	5440108.40	2.40	27/10/1981
6627	3003	2265463.60	5441702.20	15.00	19/10/1981
6629	3004	2262941.60	5436190.20	65.60	8/02/1982
6631	3005	2263842.80	5435291.40	5.80	14/11/1981
6633	3006	2267818.00	5443624.00	18.40	30/10/1981
6635	3007	2263265.00	5436253.80	51.00	15/02/1982
6637	3008	2267644.00	5440284.20	117.60	22/10/1981
6639	3009	2266952.80	5437663.00	127.40	21/11/1980
6641	3010	2267847.80	5436062.00	77.80	7/12/1981
6643	3011	2266781.40	5434745.80	67.60	16/12/1981
6645	3012	2268802.60	5434622.60	27.00	12/12/1981
6647	3013	2269959.40	5433150.20	101.60	2/12/1981
6649	3014	2273672.80	5438898.20	165.40	1/02/1982
6651	3015	2276393.80	5439514.60	122.00	22/01/1982
6653	3016	2276637.20	5441998.80	116.60	26/01/1982
6655	3017	2279816.40	5443312.00	110.00	20/01/1982
6657	3018	2266801.00	5433870.40	9.20	4/02/1982
6659	3019	2263793.20	5433970.80	9.20	2/05/1982
6661	3020	2263987.40	5440006.00	1.00	22/02/1982
6663	3021	2263355.60	5437150.80	1.80	22/02/1982
6665	3022	2265489.40	5434818.60	1.20	3/02/1982
6667	3023	2269461.00	5433758.80	92.60	8/03/1982
6669	3024	2269174.40	5433142.00	113.20	22/04/1982
6671	3025	2269188.50	5433378.00	82.00	2/01/1980
6673	3026	2270884.40	5432417.00	98.40	1/04/1982
6675	3027	2270885.80	5432510.60	108.20	22/04/1982
6677	3028	2271070.10	5433849.58	100.24	1/02/1983
6679	3029	2270965.10	5435585.56	146.21	29/01/1983
6681	3030	2264564.80	5435231.29	1.69	24/02/1983
6683	3031	2264043.30	5438960.70	1.31	4/09/1983
6685	3032	2265275.20	5437463.10	2.71	20/04/1983
6687	3033	2267990.80	5434823.80	15.67	10/03/1983
6689	3034	2270041.80	5435004.56	126.23	17/03/1983
6691	3035	2267076.20	5435916.22	85.74	17/03/1983
6693	3036	2269587.60	5434392.94	76.93	5/03/1983
6695	3037	2268747.50	5435603.21	29.48	Unknown
6697	3038	2271559.10	5434494.46	85.00	18/03/1983
6699	3039	2269020.60	5436555.30	73.38	9/03/1983
6701	3040	2265022.20	5433273.85	1.28	3/08/1983
6703	3041	2271030.60	5429246.58	30.59	17/03/1983
6705	3042	2272578.80	5433881.09	82.68	29/03/1983
6707	3043	2272161.60	5430951.22	28.14	24/03/1983
6709	3044	2263020.50	5434611.26	3.85	25/03/1983
6711	3045	2272113.00	5436512.00	83.37	12/04/1983
6713	3046	2262987.40	5435443.31	7.11	25/04/1983
6715	3047	2272503.50	5434929.02	123.54	14/05/1983
6717	3048	2272287.10	5433192.96	108.57	28/05/1983
6719	3049	2265539.20	5436311.76	2.78	5/05/1983

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
6721	3050	2265098.40	5438585.01	3.94	5/09/1983
6723	3051	2265877.20	5439610.75	22.37	24/05/1983
6725	3052	2265985.30	5440846.33	23.81	23/05/1983
6727	3053	2264810.40	5441194.43	2.29	27/05/1983
6729	3054	2270589.40	5432415.60	70.50	12/06/1983
6731	3055	2271637.10	5431404.30	42.00	1/01/1985
6733	3056	2272143.70	5432248.40	79.10	6/02/1985
8117	5147	2272000.00	5427500.00	0.00	Unknown
8128	5157	2272200.00	5427700.00	0.00	Unknown
8130	5158	2272010.00	5427510.00	0.00	Unknown
8148	5167	2272020.00	5427520.00	0.00	Unknown
8150	5168	2272030.00	5427530.00	0.00	Unknown
8159	5174	2272040.00	5427540.00	0.00	Unknown
8179	5190	2272050.00	5427550.00	0.00	Unknown
8181	5191	2272060.00	5427560.00	0.00	Unknown
8183	5192	2272070.00	5427570.00	0.00	Unknown
8185	5193	2272080.00	5427580.00	0.00	Unknown
8187	5194	2272090.00	5427590.00	0.00	Unknown
8189	5195	2272100.00	5427600.00	0.00	Unknown
8191	5196	2272110.00	5427610.00	0.00	Unknown
8193	5197	2272120.00	5427620.00	0.00	Unknown
8195	5198	2272130.00	5427630.00	0.00	Unknown
8197	5199	2272140.00	5427640.00	0.00	Unknown
8199	5200	2272150.00	5427650.00	0.00	Unknown
8201	5201	2272160.00	5427660.00	0.00	Unknown
8203	5202	2272170.00	5427670.00	0.00	Unknown
8219	5210	2272180.00	5427680.00	0.00	Unknown
8369	5302	2271977.40	5438183.20	45.11	2/01/1956
8371	5303	2272059.80	5438264.70	48.16	2/01/1956
8372	5304	2272096.20	5438318.80	1.00	1/01/1956
8374	5305	2272046.80	5438295.90	50.90	2/01/1956
8378	5307	2272140.60	5437983.20	42.37	Unknown
8380	5308	2272099.70	5438043.30	43.89	Unknown
8404	5320	2271938.30	5438232.30	48.16	2/01/1956
8410	5323	2271661.30	5438620.40	58.52	2/01/1956
8412	5324	2271754.80	5438613.90	70.10	2/01/1956
8418	5327	2271727.60	5438774.40	1.00	2/01/1956
8420	5328	2271740.40	5438794.40	67.06	2/01/1956
8422	5329	2271685.70	5438950.80	64.01	2/01/1956
8424	5330	2271676.70	5438789.20	55.17	2/01/1956
8426	5331	2271780.50	5439024.10	74.68	2/01/1956
8428	5332	2271915.00	5439019.80	94.79	2/01/1956
8430	5333	2271938.60	5439120.60	81.69	2/01/1956
8432	5334	2272380.00	5439033.00	89.31	2/01/1956
8434	5335	2272287.50	5439095.00	74.98	2/01/1956
8533	5386	2274002.00	5437000.00	27.73	2/01/1946
8535	5387	2274001.00	5437000.00	15.84	2/01/1946
8536	5388	2274001.00	5437000.00	7.31	2/01/1946
8540	5391	2274001.00	5437000.00	24.99	2/01/1946
8541	5392	2274001.00	5437000.00	31.08	2/01/1946
8543	5393	2274001.00	5437000.00	38.10	2/01/1946
8559	5406	2266189.50	5448712.00	30.48	Unknown

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
8561	5407	2266374.00	5448624.00	30.48	Unknown
8563	5408	0.00	0.00	121.90	Unknown
8579	5424	0.00	0.00	0.00	1/05/1984
8585	5430	0.00	0.00	0.00	1/09/1984
6735	3057	2269561.90	5429676.30	105.70	11/02/1985
6737	3058	2272822.60	5431060.90	22.50	12/02/1985
6739	3059	2271880.10	5430338.50	31.50	18/02/1985
6741	3060	2270440.30	5432907.90	104.60	25/02/1985
6743	3061	2270898.40	5428819.30	23.60	27/02/1985
6745	3062	2271530.00	5432829.40	107.70	1/03/1985
6747	3063	2268383.90	5427498.80	25.90	19/03/1985
6749	3064	2270508.40	5433602.91	47.10	25/03/1985
6750	3064R	2270508.50	5433603.00	0.00	26/03/1985
6752	3065	2268152.70	5432735.00	26.70	19/04/1985
6754	3066	2268737.40	5435062.50	57.90	1/05/1985
6756	3067	2268367.00	5434721.40	22.80	13/05/1985
6758	3068	2269409.30	5434813.00	54.80	16/05/1985
6760	3069	2271591.10	5429777.10	28.00	23/05/1985
6762	3070	2270040.20	5434307.40	161.40	5/05/1985
6793	3101	2265926.00	5439000.00	7.10	15/03/1985
6794	3102	2263711.70	5438750.70	1.00	26/02/1985
6795	3103	2264822.40	5436534.43	0.20	26/02/1985
6796	3104	2263716.40	5438889.27	0.80	26/02/1985
6797	3105	2263742.20	5438592.46	1.90	27/02/1985
6798	3106	2264028.60	5439327.00	1.00	28/02/1985
6799	3107	2266194.40	5439950.88	54.30	1/03/1985
6800	3108	2263907.70	5439282.63	1.30	1/03/1985
6801	3109	2266058.60	5437787.77	80.30	2/03/1985
6802	3110	2264825.00	5440704.00	1.80	2/03/1985
6803	3111	2264852.90	5440431.12	2.00	4/03/1985
6804	3112	2265175.40	5440861.02	10.30	6/03/1985
6805	3113	2265704.50	5438478.31	17.90	11/03/1985
6806	3114	2265075.40	5439253.17	39.60	11/03/1985
6807	3115	2264011.60	5438038.44	1.00	18/03/1985
6808	3116	2266118.70	5441802.06	29.60	15/03/1985
6809	3117	2265745.20	5438963.81	4.90	19/03/1985
6810	3118	2263943.30	5436476.34	54.00	18/03/1985
6811	3119	2262751.80	5436844.00	16.70	23/03/1985
6812	3120	2265793.90	5438956.35	5.50	1/01/1985
6813	3121	2265788.70	5438975.47	5.50	1/01/1985
6814	3122	2265920.60	5439022.72	6.80	1/01/1985
6815	3123	2263096.00	5436791.26	19.70	28/03/1985
6816	3124	2264448.00	5436045.38	5.20	1/04/1985
6817	3125	2265786.20	5438979.57	5.50	1/01/1985
6818	3126	2264820.70	5436527.44	0.20	17/04/1985
6819	3127	2265073.90	5439263.41	40.00	22/04/1985
6820	3128	2263041.60	5437638.23	38.90	13/04/1985
6821	3129	2265183.10	5435593.89	0.30	17/04/1985
6822	3130	2264815.00	5436530.00	0.20	1/02/1985
6823	3131	2265550.00	5443372.00	2.80	1/02/1985
6824	3132	2266483.00	5443436.00	17.10	1/02/1985
6825	3133	2264686.00	5436223.00	0.60	1/02/1985

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
6826	3134	2264915.00	5435021.00	1.30	1/02/1985
7894	5001	2266223.50	5436003.50	16.76	1/02/1956
7896	5002	2266497.70	5436007.50	22.86	1/02/1956
7898	5003	2266397.20	5436555.00	15.24	1/02/1956
7907	5011	2268765.00	5434088.00	47.55	1940-1950's
7909	5012	2268894.00	5433998.00	46.63	1940-1950's
7911	5013	2268930.00	5433909.00	52.12	1940-1950's
7913	5014	2268880.00	5433878.00	64.01	1940-1950's
7915	5015	2268666.00	5433855.00	57.61	1940-1950's
7917	5016	2268285.90	5434542.00	23.47	1940-1950's
7919	5017	2268405.00	5433852.00	99.36	1940-1950's
7920	5018	2268445.00	5433866.00	85.04	1940-1950's
7922	5019	2268421.00	5433721.00	96.93	1940-1950's
7924	5020	2268329.00	5434109.00	83.52	1940-1950's
7926	5021	2268413.00	5434006.00	78.94	1940-1950's
7928	5022	2268374.00	5433866.00	104.24	1940-1950's
7930	5023	2268410.00	5433753.00	93.27	1940-1950's
7932	5024	2268444.00	5433624.00	93.57	1940-1950's
7934	5025	2268512.00	5433571.00	112.78	1940-1950's
7936	5026	2268781.00	5434094.00	30.48	1940-1950's
7938	5027	2268803.00	5434113.00	27.43	1940-1950's
7942	5030	2269060.00	5432680.00	59.74	1940-1950's
7944	5031	2269076.00	5432676.00	62.18	1940-1950's
7946	5032	2269090.00	5432670.00	64.01	1940-1950's
7948	5033	2269058.00	5432653.00	60.96	1940-1950's
7950	5034	2269072.00	5432652.00	58.83	1940-1950's
7951	5035	2269052.00	5432667.00	59.13	1940-1950's
7953	5036	2269122.00	5432658.00	67.97	1940-1950's
7955	5037	2269109.00	5432623.00	62.18	1940-1950's
7957	5038	2269091.00	5432579.00	61.26	1940-1950's
7959	5039	2269108.00	5432583.00	62.18	1940-1950's
7961	5040	2269134.00	5432582.00	67.67	1940-1950's
7962	5041	2269039.00	5432647.00	48.16	1940-1950's
7963	5042	2269307.00	5432532.00	88.39	1940-1950's
7964	5043	2269334.00	5432571.00	88.70	1940-1950's
7966	5044	2269316.00	5432544.00	90.53	1940-1950's
7967	5045	2269292.00	5432560.00	86.26	1940-1950's
7969	5046	2269312.00	5432565.00	90.53	1940-1950's
7971	5047	2269325.00	5432556.00	90.83	1940-1950's
7973	5048	2269317.00	5432575.00	89.31	1940-1950's
7975	5049	2269292.00	5432591.00	90.83	1940-1950's
7977	5050	2269307.00	5432590.00	89.61	1940-1950's
7979	5051	2269395.00	5432515.00	103.02	1940-1950's
7981	5052	2269359.00	5432462.00	0.00	1940-1950's
7983	5053	2269394.00	5432540.00	103.63	1940-1950's
7985	5054	2269459.00	5432465.00	114.00	1940-1950's
7987	5055	2269341.00	5432494.00	90.83	1940-1950's
7989	5056	2268837.00	5432292.00	105.77	1940-1950's
7991	5057	2268868.00	5432312.00	105.16	1940-1950's
7993	5058	2268859.00	5432321.00	103.94	1940-1950's
7995	5059	2268846.00	5432331.00	103.33	1940-1950's
7997	5060	2268833.00	5432328.00	105.77	1940-1950's

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
7999	5061	2270810.00	5432218.00	89.92	1940-1950's
8001	5062	2270796.00	5432282.00	75.59	1940-1950's
8003	5063	2270794.00	5432273.00	77.11	1940-1950's
8005	5064	2270809.00	5432251.00	78.64	1940-1950's
8007	5065	2270819.00	5432131.00	93.57	1940-1950's
8009	5066	2270745.00	5432153.00	90.22	1940-1950's
8011	5067	2270743.00	5432199.00	84.73	1940-1950's
8013	5068	2270791.00	5432132.00	99.36	1940-1950's
8015	5069	2270820.00	5432142.00	92.35	1940-1950's
8017	5070	2270792.00	5432282.00	75.29	1940-1950's
8019	5071	2270733.00	5432286.00	76.50	1940-1950's
8021	5072	2270529.00	5432306.00	71.63	1940-1950's
8023	5073	2270830.00	5432302.00	74.98	1940-1950's
8025	5074	2270500.00	5432324.00	89.00	1940-1950's
8027	5075	2270496.00	5432310.00	89.31	1940-1950's
8029	5076	2270522.00	5432321.00	87.78	1940-1950's
8031	5077	2270536.00	5432329.00	88.09	1940-1950's
8033	5078	2270542.00	5432312.00	88.39	1940-1950's
8035	5079	2270492.00	5432337.00	92.05	1940-1950's
8037	5080	2270472.00	5432327.00	91.14	1940-1950's
8039	5081	2270455.00	5432323.00	90.83	1940-1950's
8041	5082	2270455.00	5432310.00	90.83	1940-1950's
8043	5083	2270534.00	5432358.00	91.74	1940-1950's
8044	5084	2270529.00	5432362.00	93.88	1940-1950's
8046	5085	2270526.00	5432386.00	97.23	1940-1950's
8047	5086	2270723.00	5431963.00	124.36	1940-1950's
8048	5087	2270712.00	5432003.00	107.90	1940-1950's
8049	5088	2270825.00	5432382.00	78.33	1940-1950's
8051	5089	2270826.00	5432320.00	74.68	1940-1950's
8053	5090	2269931.00	5433399.00	60.19	1940-1950's
8055	5091	2269862.00	5433280.00	63.54	1940-1950's
8057	5092	2269806.00	5433168.00	72.43	1940-1950's
8059	5093	2269770.00	5433088.00	84.30	1940-1950's
8061	5094	2269710.00	5433078.00	89.64	1940-1950's
8063	5095	2269598.00	5433039.00	91.79	1940-1950's
8065	5096	2269538.00	5433015.00	100.43	1940-1950's
8066	5097	2269544.00	5433065.00	89.53	1940-1950's
8067	5098	2269491.00	5433011.00	97.89	1940-1950's
8068	5099	2269467.00	5433073.00	93.65	1940-1950's
8070	5100	2269403.00	5433030.00	99.67	1940-1950's
8072	5101	2269549.00	5433119.00	77.77	1940-1950's
8073	5102	2269570.00	5433110.00	80.99	1940-1950's
8074	5103	2269718.00	5433162.00	68.12	1940-1950's
8075	5104	2269721.00	5433135.00	77.16	1940-1950's
8076	5105	2269770.00	5433195.00	66.47	1940-1950's
8077	5106	2269778.00	5433177.00	70.56	1940-1950's
8078	5107	2269790.70	5433321.30	64.41	1940-1950's
8079	5108	2269826.40	5433348.60	63.70	1940-1950's
8080	5109	2269831.00	5433209.00	66.24	1940-1950's
8081	5110	2269887.00	5433209.00	71.68	1940-1950's
8082	5111	2269906.00	5433330.00	61.69	1940-1950's
8083	5112	2269772.00	5433165.00	78.50	1940-1950's

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
8084	5113	2269723.00	5433129.00	81.71	1940-1950's
8085	5114	2269645.00	5433111.00	82.32	1940-1950's
8086	5115	2269602.00	5433107.00	81.91	1940-1950's
8087	5116	2269616.00	5433143.00	74.16	1940-1950's
8088	5117	2269515.00	5433105.00	82.98	1940-1950's
8089	5120	2269788.00	5432925.00	88.75	1940-1950's
8090	5121	2269831.00	5432937.00	84.60	1940-1950's
8091	5122	2269860.00	5432927.00	89.31	1940-1950's
8092	5123	2269904.00	5432947.00	81.74	1940-1950's
8093	5124	2269933.00	5432922.00	86.66	1940-1950's
8094	5125	2269897.00	5432974.00	77.89	1940-1950's
8095	5126	2269944.00	5432968.00	79.44	1940-1950's
8096	5127	2269931.00	5432982.00	75.01	1940-1950's
8097	5128	2269916.00	5433016.00	81.76	1940-1950's
8098	5129	2269977.00	5432995.00	73.15	1940-1950's
8099	5130	2269978.00	5432982.00	75.97	1940-1950's
8100	5131	2270020.00	5433015.00	69.80	1940-1950's
8101	5132	2270024.00	5432997.00	72.13	1940-1950's
8102	5133	2270029.00	5432979.00	75.48	1940-1950's
8103	5134	2270011.00	5433008.00	77.80	1940-1950's
8104	5135	2269992.00	5432923.00	82.67	1940-1950's
8105	5136	2270061.00	5432916.00	80.64	1940-1950's
8106	5137	2270061.90	5433100.60	69.90	1940-1950's
8107	5138	2270044.00	5433052.00	70.76	1940-1950's
8108	5139	2270046.60	5433135.70	67.97	1940-1950's
8109	5140	2270136.00	5433014.00	64.01	1940-1950's
8110	5141	2270147.00	5433002.00	67.86	1940-1950's
8111	5142	2270188.00	5433043.00	62.37	1940-1950's
8112	5143	2270203.00	5433015.00	64.95	1940-1950's
8113	5144	2270268.00	5433035.00	61.16	1940-1950's
8114	5145	2270223.60	5433177.70	64.51	1940-1950's
8115	5146	2270617.00	5432049.00	131.98	1940-1950's
8124	5155	2267333.00	5427766.00	71.32	1940-1950's
8126	5156	2267308.00	5427748.00	67.36	1940-1950's
8132	5159	2267306.00	5427780.00	67.97	1940-1950's
8134	5160	2267285.00	5427707.00	62.18	1940-1950's
8136	5161	2267489.00	5428242.00	75.59	1940-1950's
8138	5162	2267477.00	5428311.00	76.81	1940-1950's
8140	5163	2267597.00	5428169.00	65.53	1940-1950's
8142	5164	2267664.00	5428098.00	55.78	1940-1950's
8144	5165	2267731.00	5428035.00	43.28	1940-1950's
8146	5166	2267821.00	5427991.00	35.66	1940-1950's
8152	5169	2267230.00	5427822.00	0.00	1940-1950's
8154	5170	2267235.00	5427677.00	46.94	1940-1950's
8161	5175	2267854.00	5428041.00	33.53	1940-1950's
8163	5176	2267950.00	5428216.00	42.37	1940-1950's
8164	5177	2267908.00	5428231.00	42.37	1940-1950's
8172	5185	2267193.00	5427759.00	73.76	1940-1950's
8174	5186	2267190.00	5427622.00	67.36	1940-1950's
8205	5203	2267110.00	5427990.00	96.32	1940-1950's
8207	5204	2267062.00	5427975.00	85.95	1940-1950's
8209	5205	2267023.00	5427951.00	89.92	1940-1950's

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
8211	5206	2267039.00	5428025.00	99.67	1940-1950's
8213	5207	2267070.00	5427995.00	94.49	1940-1950's
8215	5208	2267019.00	5428061.00	108.81	1940-1950's
8217	5209	2267004.00	5428055.00	109.42	1940-1950's
8221	5211	2267112.00	5428147.00	99.67	1940-1950's
8223	5212	2267113.00	5428126.00	107.59	1940-1950's
8225	5213	2266972.00	5428198.10	0.00	1940-1950's
8227	5214	2267196.00	5428160.00	106.98	1940-1950's
8229	5215	2270808.00	5430579.00	49.68	1940-1950's
8231	5216	2270113.00	5429851.00	56.69	1940-1950's
8233	5217	2268934.00	5432039.00	91.44	1940-1950's
8235	5218	2270048.00	5431490.00	76.20	1940-1950's
8238	5220	2263500.00	5438500.00	18.00	2/01/1956
8242	5223	2267412.20	5430628.50	6.40	1/09/1985
8244	5224	2268961.00	5431555.00	99.36	1940-1950's
8246	5225	2268988.00	5431855.00	118.26	1940-1950's
8250	5228	2267258.70	5428889.00	123.44	1940-1950's
8252	5229	2267441.50	5428891.50	117.65	1940-1950's
8257	5233	2267505.20	5430539.00	79.55	1940-1950's
8259	5234	2267596.70	5430540.50	81.38	1940-1950's
8261	5235	2267598.00	5430449.00	96.93	1940-1950's
8263	5236	2267691.20	5430359.50	114.60	1940-1950's
8265	5237	2267599.70	5430357.50	105.16	1940-1950's
8267	5238	2267606.00	5429992.00	124.97	1940-1950's
8269	5239	2267694.50	5430176.50	127.41	1940-1950's
8271	5240	2267601.20	5430266.50	112.17	1940-1950's
8273	5241	2267599.70	5430357.50	103.94	1940-1950's
8275	5242	2267598.00	5430449.00	87.78	1940-1950's
8277	5243	2267598.00	5430449.00	87.78	1940-1950's
8279	5244	2267319.20	5430718.50	30.48	1940-1950's
8281	5245	2267332.00	5428523.00	104.85	1940-1950's
8283	5246	2267340.00	5428310.00	89.61	1940-1950's
8285	5247	2266456.00	5427686.00	5.18	1940-1950's
8287	5248	2270718.70	5429770.50	42.67	1940-1950's
8289	5249	2269928.10	5429831.32	64.62	1940-1950's
8291	5250	2270344.90	5429820.13	53.95	1940-1950's
8293	5251	2270250.70	5430402.50	62.18	1940-1950's
8295	5252	2270616.20	5430409.00	54.25	1940-1950's
8297	5253	2270425.70	5430862.50	58.52	1940-1950's
8299	5254	2269876.00	5430945.00	75.90	1940-1950's
8301	5255	2269348.30	5429830.81	79.55	1940-1950's
8303	5256	2268946.00	5431843.50	117.35	1940-1950's
8305	5257	2268665.70	5432204.50	63.09	1940-1950's
8307	5258	2268977.80	5432674.93	41.45	1940-1950's
8309	5259	2270879.20	5430107.34	65.00	1940-1950's
8311	5260	2270559.40	5430042.59	90.00	1940-1950's
8313	5261	2269729.90	5429544.85	145.00	1940-1950's
8315	5262	2269259.00	5429563.00	164.59	1940-1950's
8317	5263	2270075.70	5429555.90	86.56	1940-1950's
8319	5264	2270278.90	5429435.83	63.70	1940-1950's
8321	5265	2269674.40	5429770.69	78.33	1940-1950's
8323	5266	2270133.80	5430069.02	98.76	1940-1950's

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
8325	5267	2269751.10	5430079.30	118.57	1940-1950's
8327	5268	2269631.00	5429203.50	64.62	1940-1950's
8329	5269	2269262.20	5429380.00	93.27	1940-1950's
8331	5270	2268997.20	5428826.50	89.00	1940-1950's
8333	5271	2268810.00	5429097.50	105.16	1940-1950's
8335	5272	2268531.00	5429367.50	123.75	1940-1950's
8337	5273	2263560.00	5437068.00	5.00	1/01/1965
8341	5276	2262189.00	5437242.00	10.00	1/01/1965
8343	5277	2263400.00	5438200.00	24.00	1/01/1965
8367	5301	2271251.00	5432435.00	67.06	1940-1950's
8376	5306	2271900.70	5438018.30	44.20	1940-1950's
8382	5309	2271560.90	5438215.30	1.00	2/01/1956
8384	5310	2271472.20	5438132.80	52.43	2/01/1956
8386	5311	2271332.20	5438068.40	56.39	1940-1950's
8388	5312	2271407.10	5438115.50	52.73	1940-1950's
8390	5313	2271611.10	5438137.60	53.04	2/01/1965
8392	5314	2271503.20	5438256.50	55.47	2/01/1956
8394	5315	2271448.10	5438354.00	59.13	2/01/1956
8396	5316	2271478.10	5438361.40	1.00	2/01/1956
8398	5317	2271437.70	5438373.50	60.05	2/01/1956
8400	5318	2271381.20	5438480.90	0.00	2/01/1956
8402	5319	2271386.10	5438467.00	0.00	2/01/1956
8406	5321	2271667.40	5438270.90	50.90	2/01/1956
8408	5322	2271839.10	5438227.40	48.77	2/01/1956
8414	5325	2271630.00	5438532.10	62.18	2/01/1956
8416	5326	2271576.40	5438429.20	52.43	2/01/1956
8436	5336	2270873.00	5432308.00	43.89	1940-1950's
8438	5337	2270861.00	5432270.00	79.25	1940-1950's
8440	5338	2270897.00	5432229.00	89.31	1940-1950's
8442	5339	2270849.00	5432166.00	93.27	1940-1950's
8444	5340	2270870.00	5432175.00	95.71	1940-1950's
8446	5341	2270885.00	5432193.00	94.18	1940-1950's
8448	5342	2270864.00	5432150.00	99.97	1940-1950's
8450	5343	2270902.00	5432207.00	93.57	1940-1950's
8452	5344	2270856.00	5432178.00	89.31	1940-1950's
8454	5345	2270876.00	5432262.00	81.38	1940-1950's
8456	5346	2270920.00	5432215.00	93.57	1940-1950's
8458	5347	2270867.00	5432304.00	74.37	1940-1950's
8460	5348	2270994.00	5432319.00	73.46	1940-1950's
8462	5349	2270962.00	5432292.00	79.25	1940-1950's
8464	5350	2271104.00	5432320.00	75.29	1940-1950's
8466	5351	2270936.00	5432261.00	85.04	1940-1950's
8468	5352	2271038.00	5432327.00	70.41	1940-1950's
8470	5353	2271039.20	5432428.00	75.59	1940-1950's
8472	5354	2271089.00	5432386.00	68.88	1940-1950's
8474	5355	2271135.00	5432234.00	80.47	1940-1950's
8476	5356	2270849.00	5432093.00	103.63	1940-1950's
8478	5357	2270857.00	5432112.00	107.59	1940-1950's
8480	5358	2270954.00	5432193.00	99.36	1940-1950's
8482	5359	2270888.00	5432128.00	107.59	1940-1950's
8484	5360	2270845.00	5432122.00	98.76	1940-1950's
8486	5361	2271392.00	5432472.00	45.11	1940-1950's

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
8488	5362	2271498.00	5432635.00	43.59	1940-1950's
8490	5363	2270916.00	5432372.00	71.93	1940-1950's
8492	5364	2271048.00	5432400.00	69.80	1940-1950's
8494	5365	2271008.00	5432367.00	72.24	1940-1950's
8496	5366	2271506.00	5431600.00	85.34	1940-1950's
8498	5367	2271450.00	5431592.00	73.76	1940-1950's
8500	5368	2271420.00	5431594.00	76.50	1940-1950's
8502	5369	2271363.00	5431573.00	83.82	1940-1950's
8504	5370	2271380.00	5431656.00	92.96	1940-1950's
8506	5371	2271386.00	5431711.00	93.27	1940-1950's
8508	5372	2271344.00	5431769.00	86.56	1940-1950's
8509	5373	2271310.00	5431759.00	76.81	1940-1950's
8510	5374	2271317.00	5431804.00	82.30	1940-1950's
8511	5375	2271290.00	5431808.00	74.98	1940-1950's
8513	5376	2271319.00	5431891.00	81.99	1940-1950's
8515	5377	2271286.00	5431877.00	76.50	2/01/1956
8517	5378	2271285.00	5431893.00	75.29	2/01/1956
8519	5379	2271218.00	5431867.00	86.87	2/01/1956
8521	5380	2271180.00	5431859.00	92.96	2/01/1956
8523	5381	2271241.00	5431841.00	78.94	2/01/1956
8525	5382	2271180.00	5431822.00	89.00	2/01/1956
8527	5383	2271267.00	5431889.00	77.42	2/01/1956
8529	5384	2271089.00	5431915.00	101.19	2/01/1956
8531	5385	2270975.00	5431791.00	73.15	2/01/1956
8537	5389	2271542.00	5431548.00	60.05	2/01/1956
8539	5390	2271541.00	5431560.00	61.26	2/01/1956
8545	5394	2271009.00	5432142.00	115.21	2/01/1956
8546	5396	2270913.00	5432296.00	75.29	2/01/1956
8550	5401	2266307.00	5441856.00	24.38	00000000
8552	5402	2266953.00	5441502.00	45.92	1940-1950's
8554	5403	2266681.70	5441314.50	45.72	00000000
8556	5404	2267963.70	5446547.50	42.67	00000000
8564	5409	2268964.00	5433224.00	97.50	7/04/1982
8565	5410	2269063.00	5432917.00	0.00	18/04/1982
8566	5411	2269030.00	5432939.00	102.90	19/04/1982
8567	5412	2268902.00	5433284.00	79.70	1/03/1983
8568	5413	2268965.00	5433291.00	76.70	15/02/1983
8569	5414	2268986.00	5433263.00	80.30	18/02/1983
8570	5415	2269084.00	5433086.00	68.70	28/02/1983
8571	5416	2268724.00	5433152.00	99.10	25/03/1983
8572	5417	2268838.00	5433266.00	78.90	1/04/1983
8573	5418	2269400.00	5433508.00	74.80	25/05/1983
8574	5419	2268909.00	5433012.00	63.10	2/06/1983
8575	5420	2268888.00	5432971.00	57.20	8/06/1983
8576	5421	2269023.00	5433322.00	71.10	1/07/1983
8577	5422	2268886.00	5433158.00	82.40	1/07/1983
8578	5423	2269100.00	5432939.00	73.70	1/08/1983
8580	5425	2268750.00	5433236.00	82.90	1/05/1984
8581	5426	2268898.00	5433202.00	92.00	1/05/1984
8582	5427	2269036.00	5433034.00	74.60	1/05/1984
8583	5428	2269087.00	5433222.00	69.00	1/08/1984
8584	5429	2269001.00	5433369.00	64.80	1/09/1984

Hole I.D.	Hole Name	Easting	Northing	Collar Elevation	Date Drilled
8586	5431	2269328.00	5433008.00	84.90	1/09/1984
8587	5432	2269578.00	5432722.00	104.80	1/11/1984
8588	5433	2269565.00	5432631.00	104.70	1/12/1984
8589	5434	2269477.00	5432607.00	99.80	2/12/1984
8590	5435	2269361.00	5432852.00	81.90	3/12/1984
8591	5436	2269349.00	5432635.00	83.90	1/01/1985
8592	5437	2269348.00	5432758.00	92.00	1/02/1985
8593	5438	2269053.00	5433406.00	85.50	2/02/1985
8594	5439	2269267.00	5433414.00	81.80	1/03/1985
8595	5440	2269111.00	5433478.00	74.00	1/03/1985
8596	5441	2268598.00	5433092.00	84.50	1/04/1985
8597	5442	2269220.00	5433166.00	99.60	1/07/1985

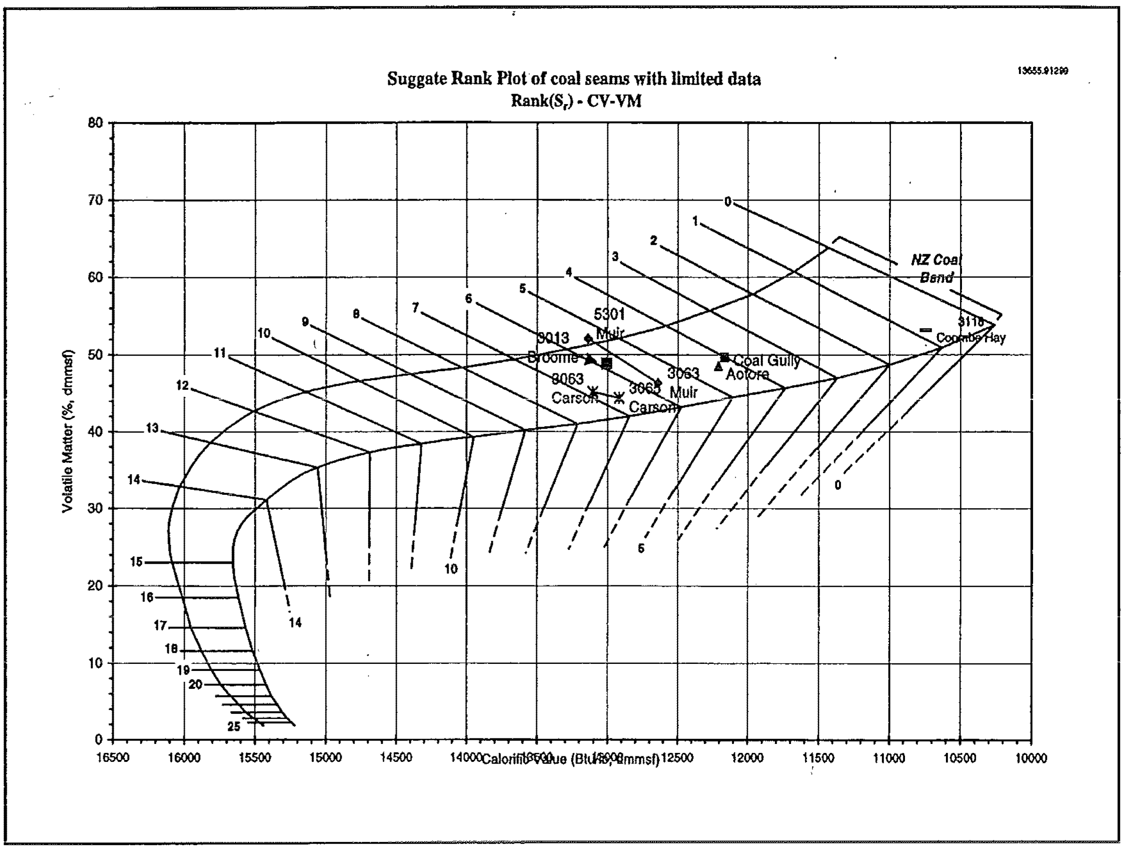
OUTCROP SAMPLES

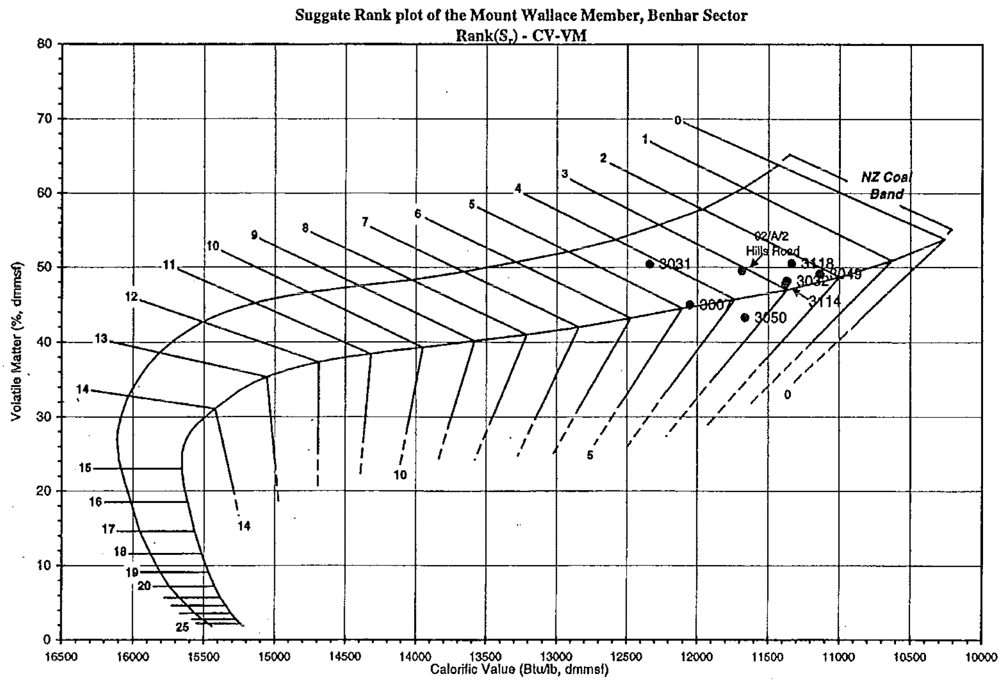
Sample	Sample Name	Easting	Northing	Elevation (AMSL)	Date Sampled
02/A/1	Hill Road	2266000	5450000	32m±4m	31/08/2002
02/A/2	Hill Road	2266000	5450000	32m±4m	31/08/2002
02/A/3	Hill Road	2266000	5450000	32m±4m	31/08/2002
02/B/1	Elliotvale Mine*	2271000	5441000	138m±8m	31/08/2002
02/B/2	Elliotvale Mine*	2271000	5441000	138m±8m	31/08/2002
CG1	Coal Gully	2278000	5450000	Unknown	2/10/2002
AOT1	Aotere (Akatore)	2290600	5452500	Unknown	2/10/2002
KPt.1	Kai Point O/Cast	22564000	5412900	~60m	3/10/2002
KPt.2	Kai Point O/Cast	22564000	5412900	~60m	4/10/2002
KPt.3	Kai Point O/Cast	22564000	5412900	~60m	5/10/2002
KPt.4	Kai Point O/Cast	22564000	5412900	~60m	6/10/2002

APPENDIX G

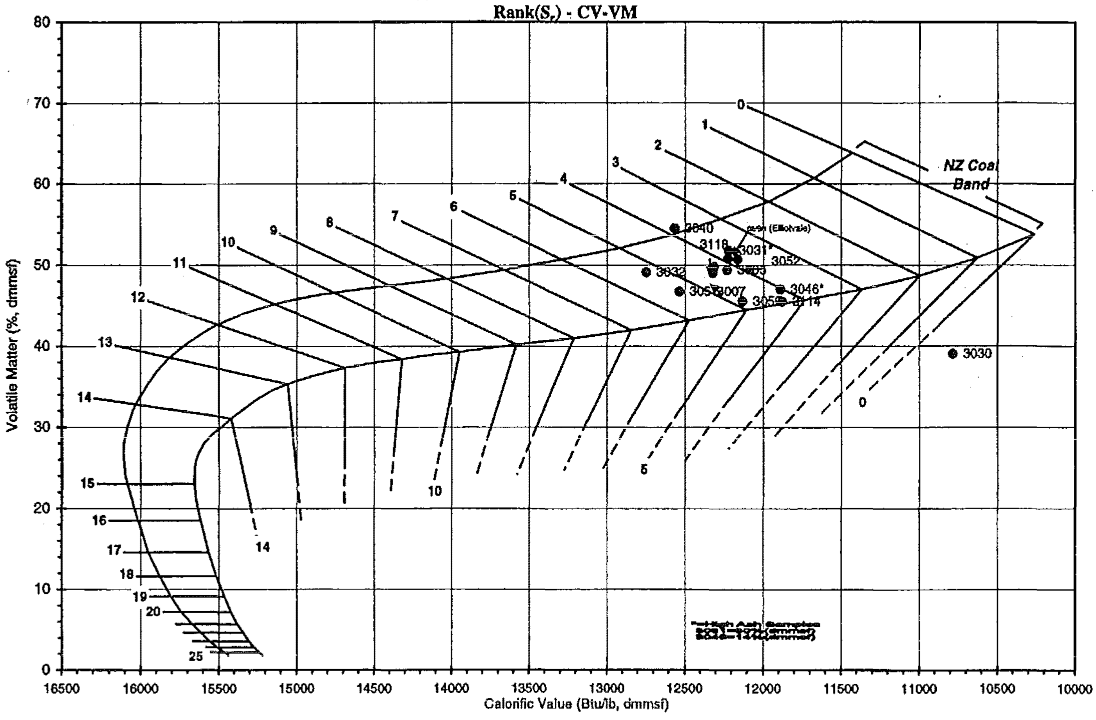
SUGGATE RANK PLOTS

APPENDIX_ SUGGATE RANK PLOTS (CV-VM) FOR TARATU FORMATION MEMBERS

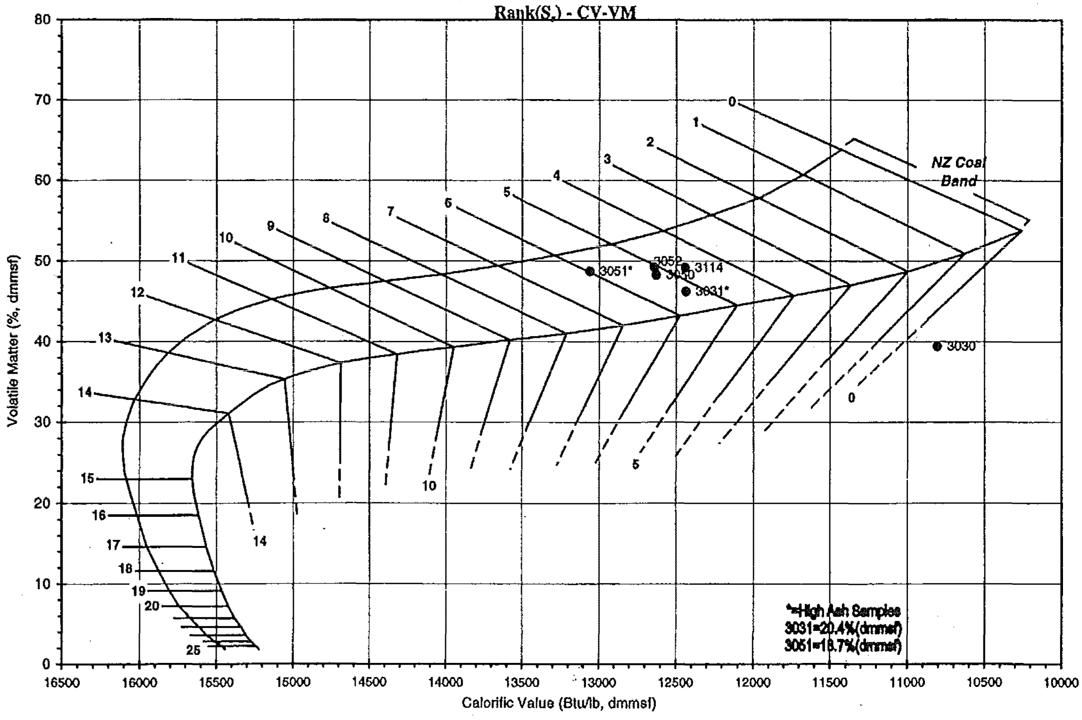




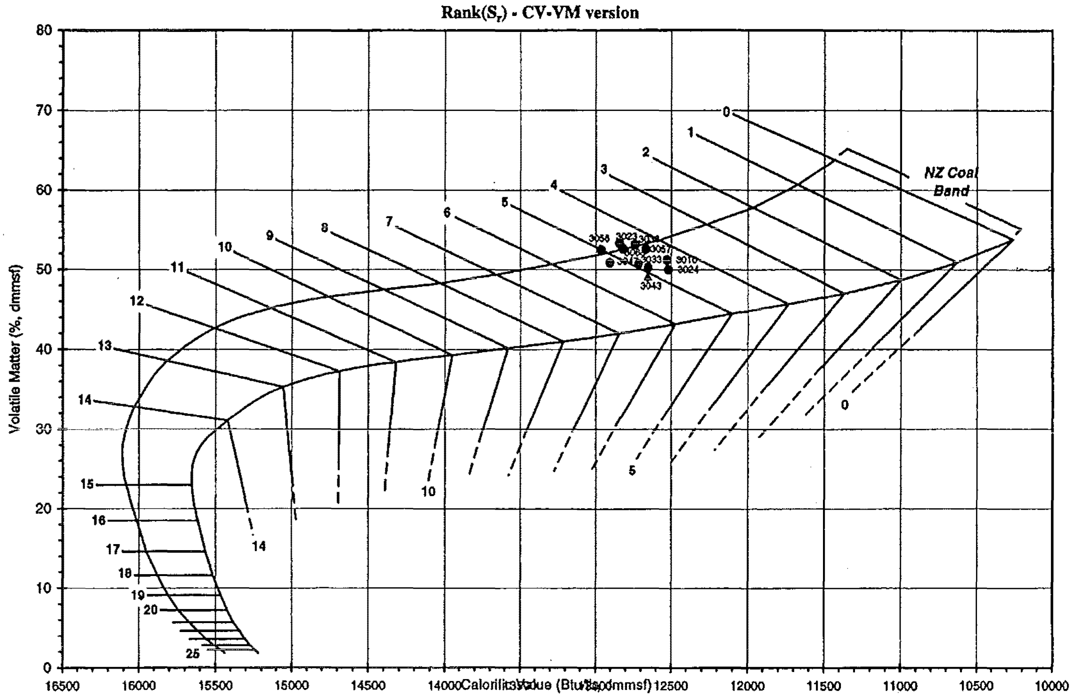
Suggate Rank plot of theBenhar Main Seams
Rank(S_r) - CV-VM



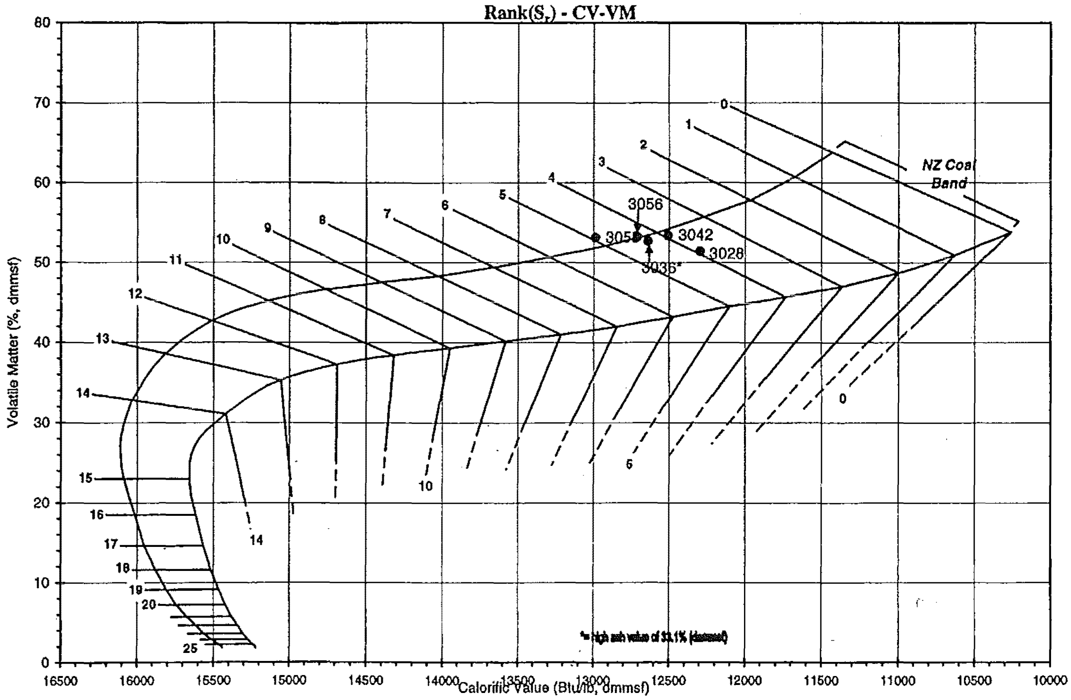
Suggate Rank plot of the Penman Member, Benhar Sector
Rank(S_r) - CV-VM



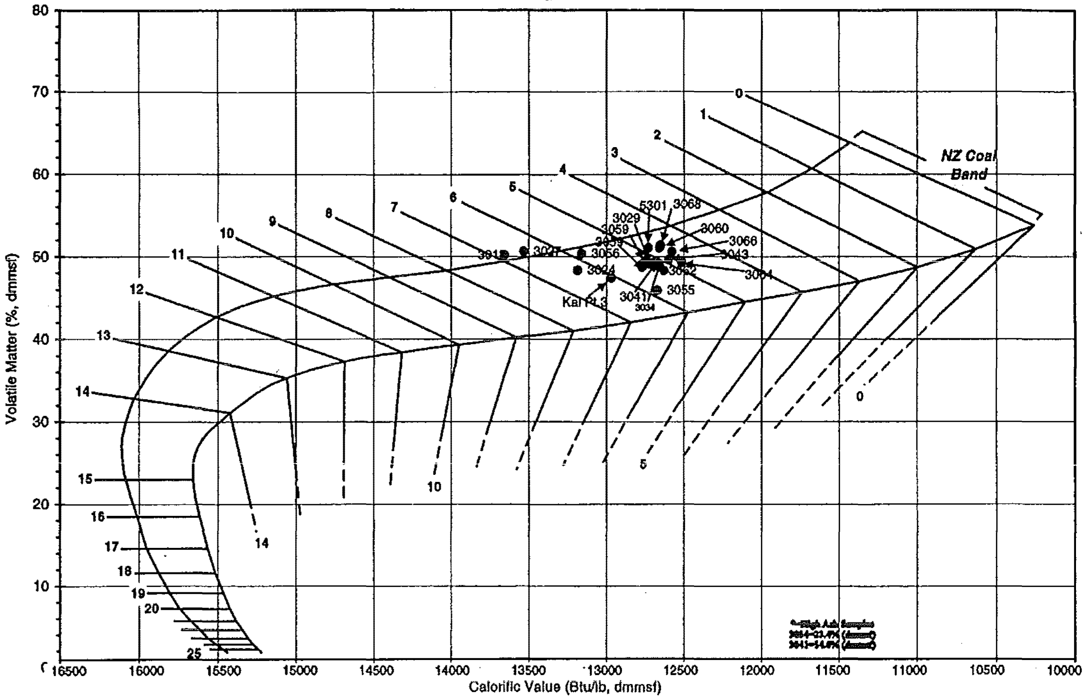
Suggate Plot of the Washpool Seams Distribution
Rank(S_r) - CV-VM version



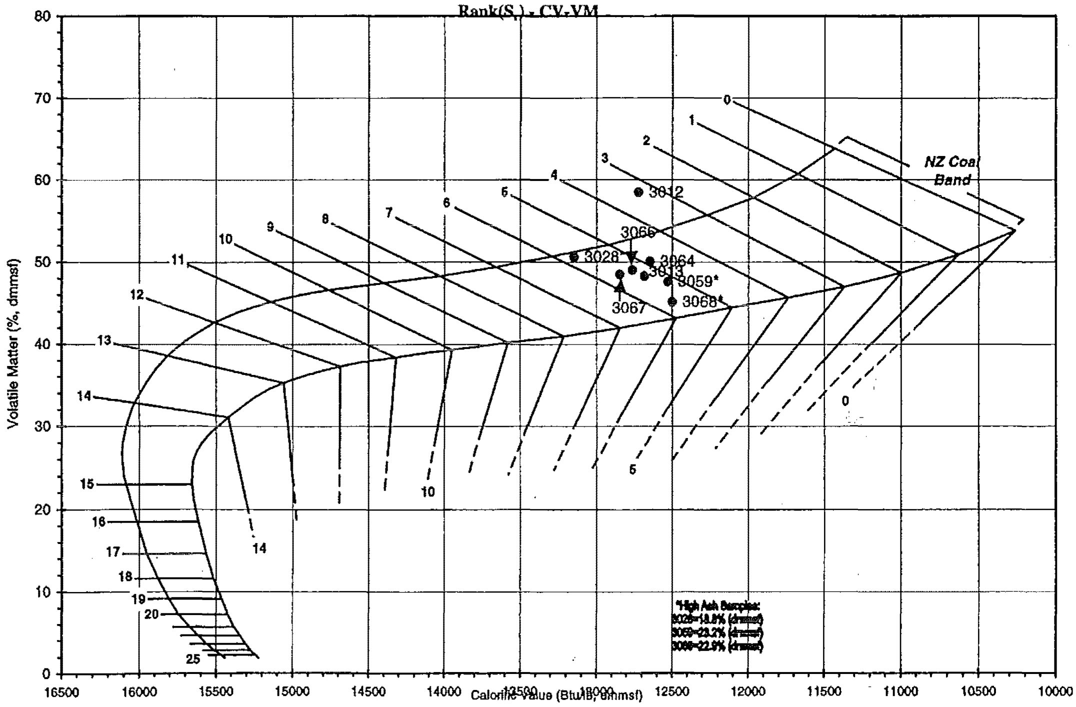
Suggate Rank Plot of the Fella Seam Distribution
Rank(S_r) - CV-VM



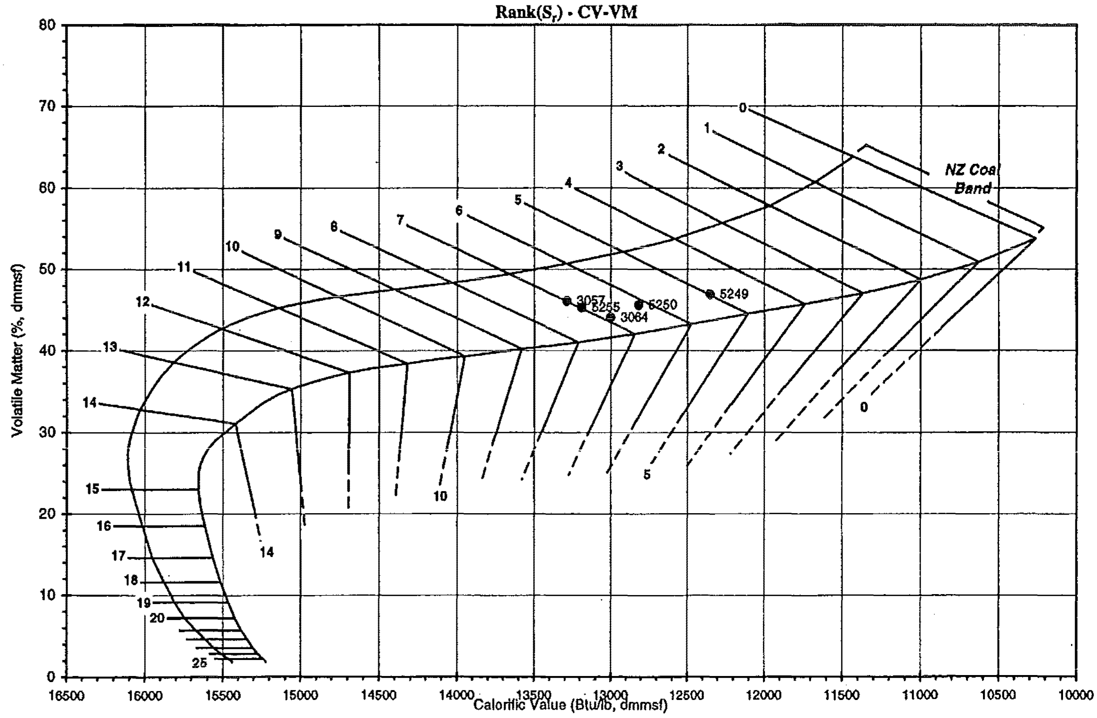
Suggate Rank Plot of the Barclay Seam Distribution
Rank(S_r) - CV-VM



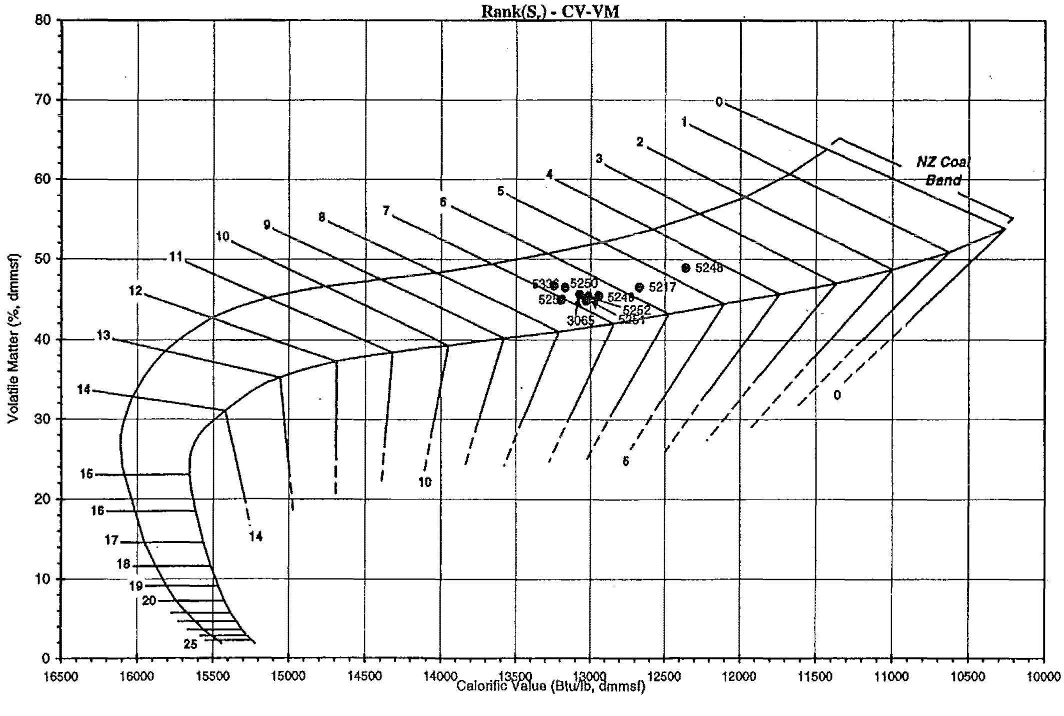
Suggate Plot of the Kaituna Seam Distribution
Rank(S_r) - CV-VM



Suggate Rank Plot of the Jordan Seam Distribution
Rank(S_r) - CV-VM

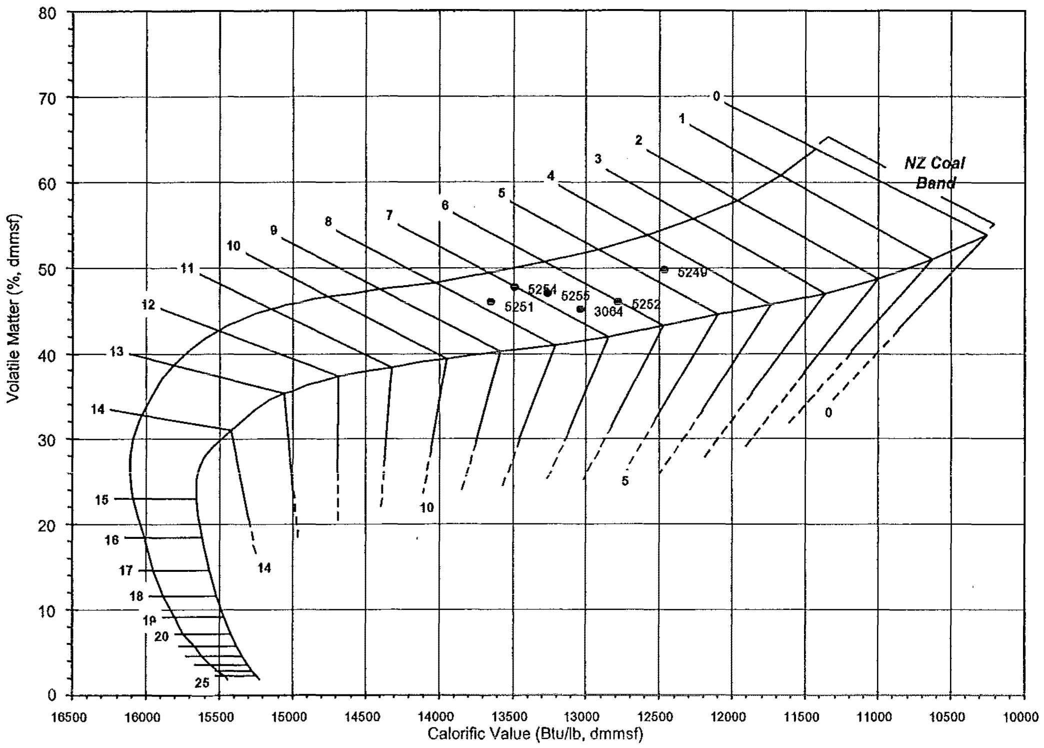


Suggate Rank Plot of the Kai-Main Seam Distribution
Rank(S_r) - CV-VM



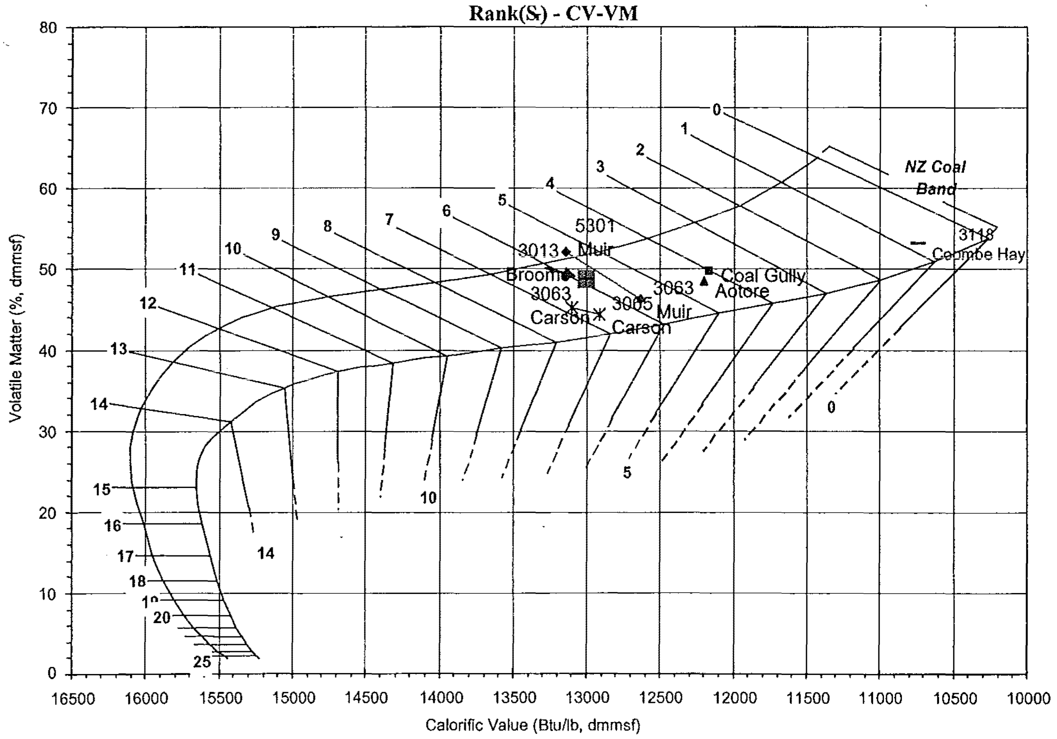
Suggate Rank Plot of the Capstick Member

Rank(S_r) - CV-VM



Suggate Rank Plot of coal seams with limited data

Rank(S_r) - CV-VM



APPENDIX H

LOGPLOT LITHOLOGICAL PATTERNS

APPENDIX H

LOGPLOT LITHOLOGICAL PATTERNS

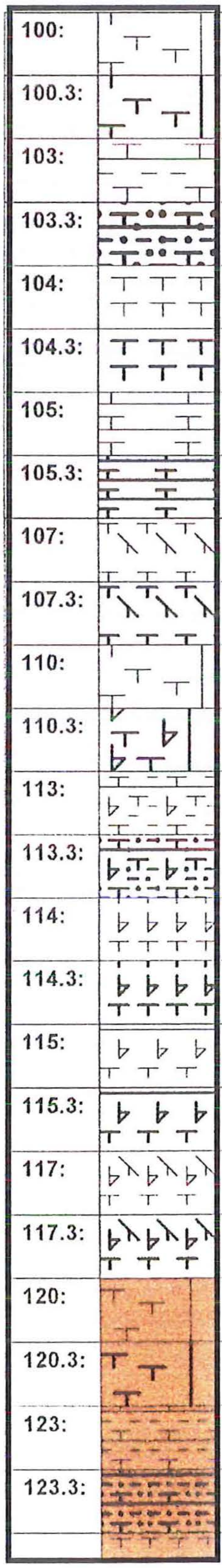
This appendix includes sheets of all the lithological patterns used in cross-sections (Appendix A) as well as the patterns used for constructing stratigraphic columns in Appendix G. A summary table (below) relates to the following sheets of lithological symbols.

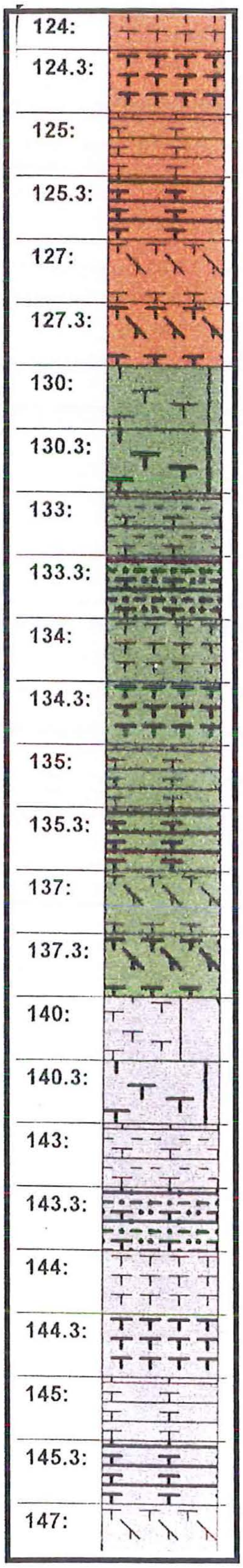
Sedimentary Rock Types and Codes Used for the Kaitangata Coalfield, New Zealand

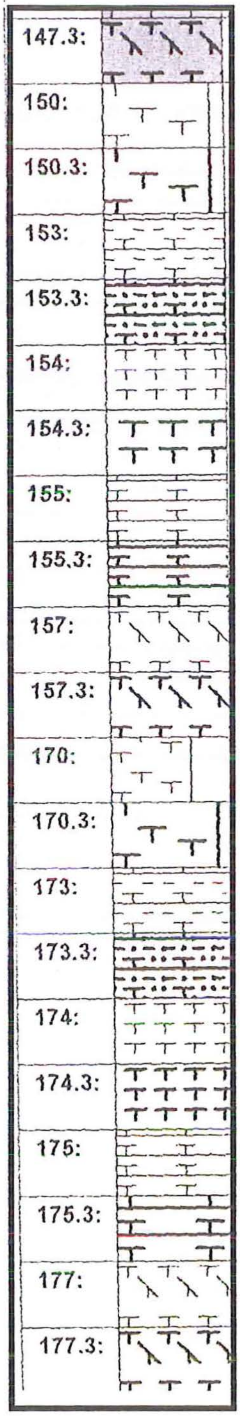
Grain size	Colour	Code	Sedmentary Features	Code
CLAYSTONE	Black	11X	Massive	1X4
CLAYSTONE	Brown	12X	Bedded	1X5
CLAYSTONE	Green	13X	Root penetration	1X7
CLAYSTONE	Grey, Dark	14X	Carbonaceous	1XX.3
CLAYSTONE	Grey, Light	15X	Interbedded with mst-silt	1X3
CLAYSTONE	Yellow	17X		
MUDSTONE/SILTSTONE	Black	31X	Massive	3X4
MUDSTONE/SILTSTONE	Brown	32X	Bedded	3X5
MUDSTONE/SILTSTONE	Green	33X	Root penetration	3X7
MUDSTONE/SILTSTONE	Grey, Dark	34X	Carbonaceous	3XX.3
MUDSTONE/SILTSTONE	Grey, Light	35X	Interbedded with ss-silt	3X3
MUDSTONE/SILTSTONE	Yellow	37X		
SANDSTONE	Green	53X	Interbedded with mst-silt	5X3
SANDSTONE	Grey, Dark	54X	Massive	5X4
SANDSTONE	Grey, Light	55X	Bedded	5X5
SANDSTONE	White	59X	Root penetration	5X7
			Carbonaceous	5XX.3
CONGLOMERATE	Green	73X	Monomictic	7X1
CONGLOMERATE	Grey, Dark	74X	Greywacke	7X1.1
CONGLOMERATE	Grey, Light	75X	Quartz	7X1.2
CONGLOMERATE	White	79X	Polymictic	7X2
			Interbedded	7X5
			Coal spars	7X3
COAL		020		
SOILS		002		
BASEMENT		003		

Based on 11 logs and a total of 573 lithological units.

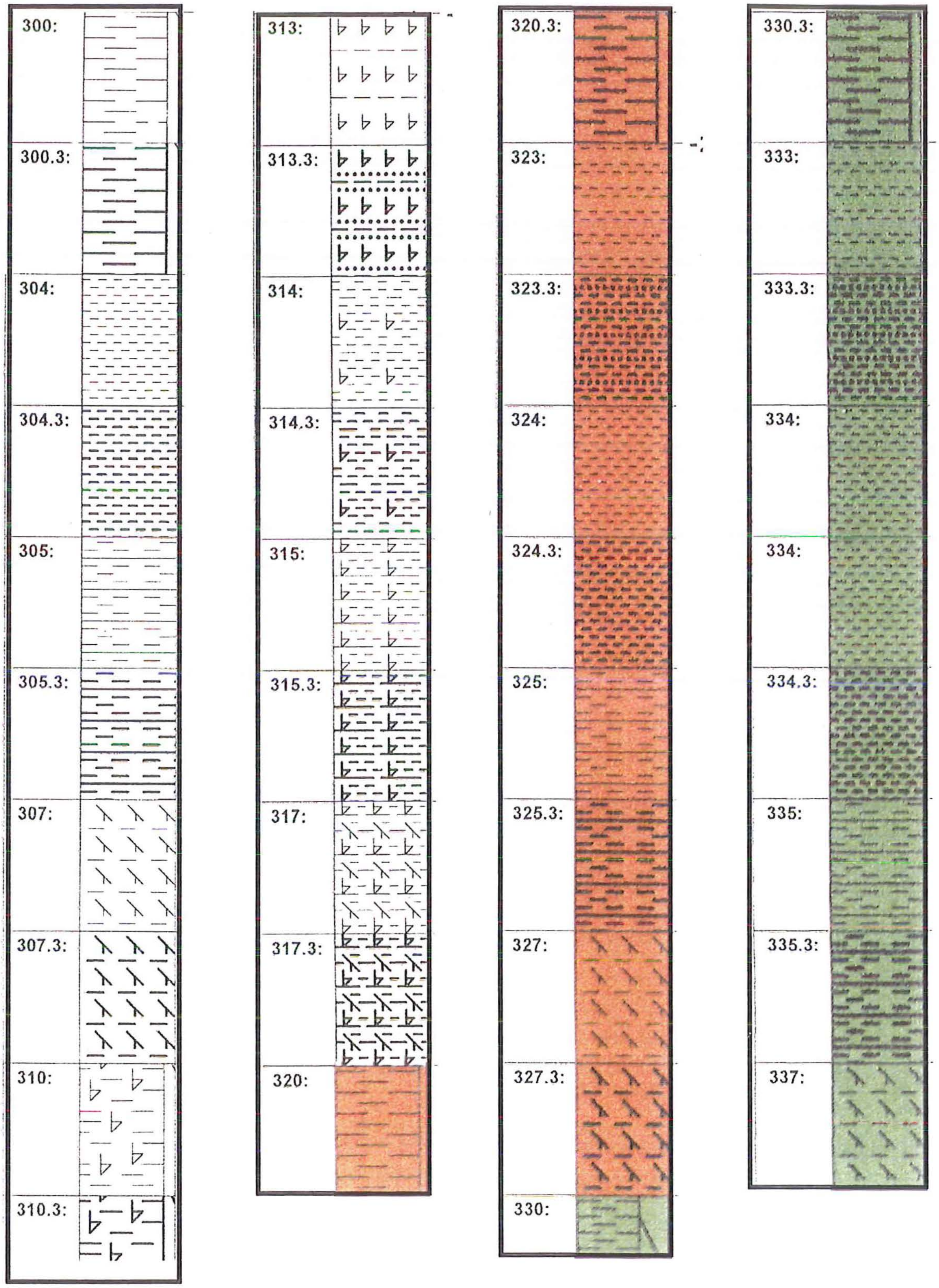
LOGPLOT LITHOLOGICAL PATTERNS FOR CLAYSTONES



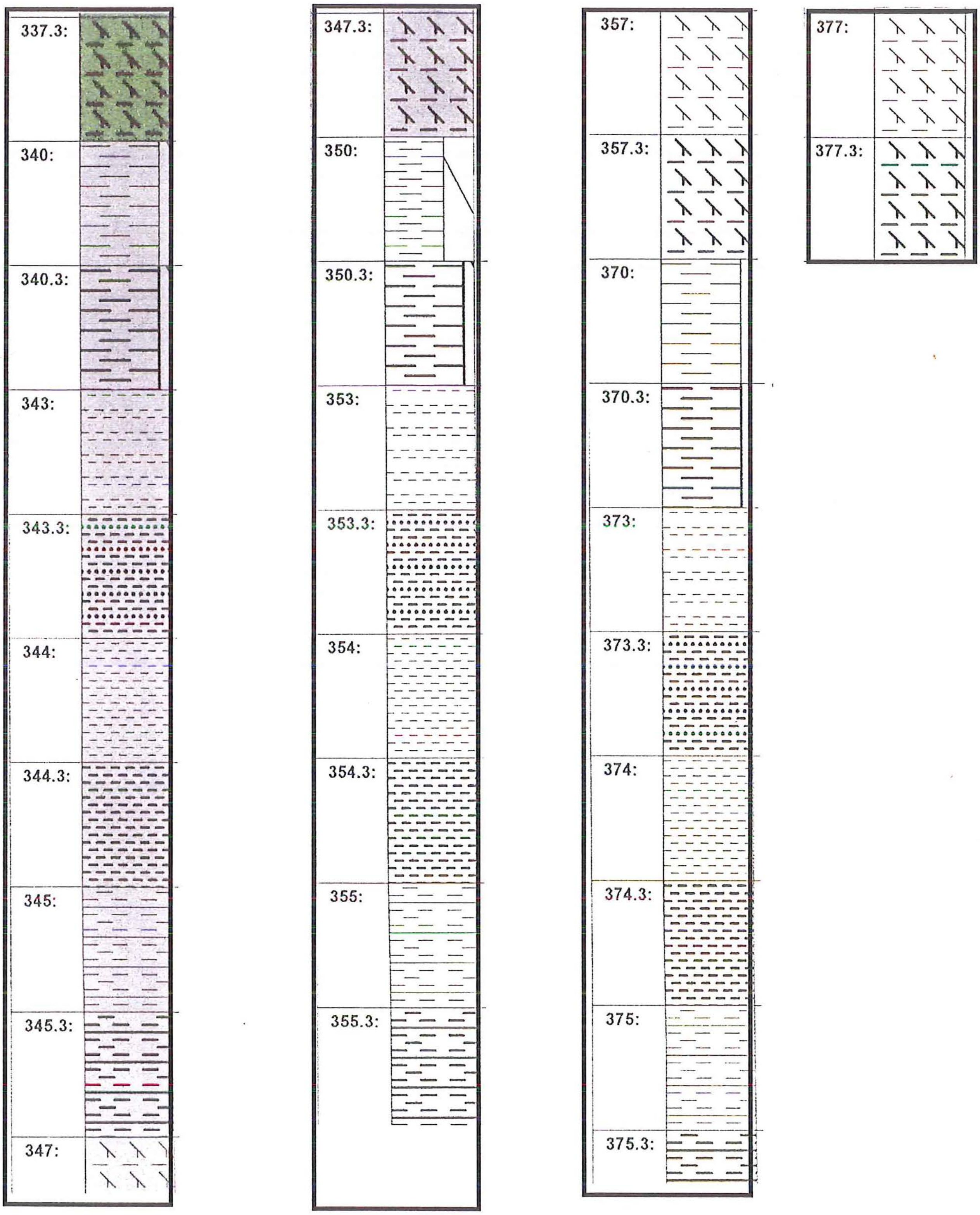




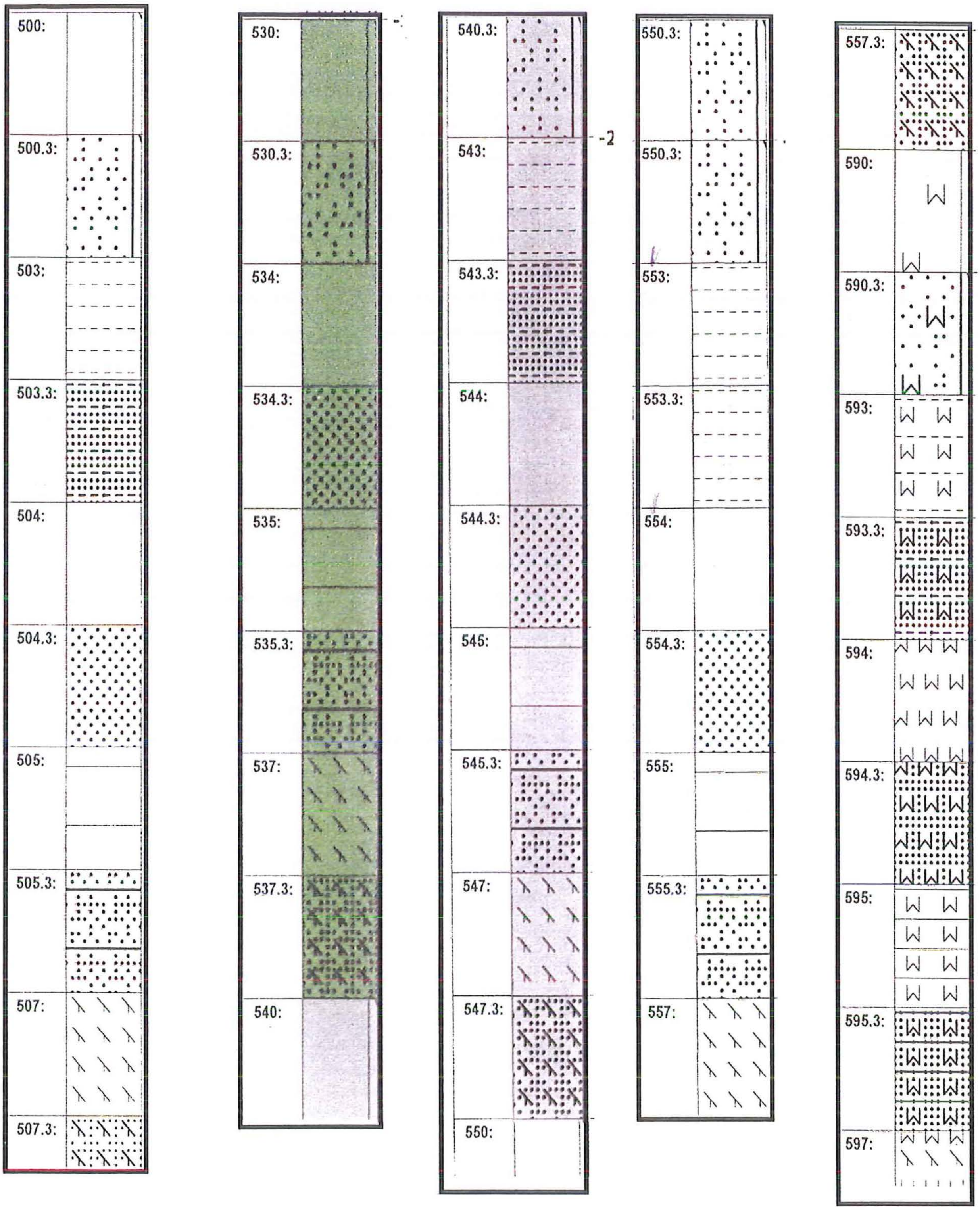
LOGPLOT LITHOLOGICAL PATTERNS FOR MUD/SILTSTONES



LOGPLOT LITHOLOGICAL PATTERNS FOR MUD/SILTSTONES



LOGPLOT LITHOLOGICAL PATTERNS FOR SANDSTONES



LOGPLOT LITHOLOGICAL PATTERNS FOR CONGLOMERATES